High-Intensity Short Duration

Light Sources

by

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An Essay

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of

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The author wishes to express his appreciation for the assistance and encouragement of Mr. Rochelle Prescott, Mr. Ben S. Melton, and Capt. E. L. Gayhart, USN (Ret) of the Applied Physics Laboratory under whose auspices the investigation reported in this paper was begun.

The photograph of the various flashlamps was very kindly supplied by the Naval Ordnance Laboratory whose personnel, especially Mr. W. T. Whelan, were most helpful in supplying much valuable information on multiple flash equipment.

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The subject of short duration high intensity light sources is one which has attained considerable importance in the last few years. Many problems under investigation today are being studied by the use of high speed photographic techniques in conjunction with various optical arrangements. Such transient phenomena as the flight of projectiles, flow lines in supersonic wind tunnels, flow lines in underwater impact, and others are being studied in this manner. Some of these problems can be investigated with the means now available. Some can be only partially explored. But on still others not even a good beginning can be made because the techniques are not yet far enough advanced.

In order to understand the attendent difficulties, it is necessary to consider some of the requirements in the making of very high speed photographs or shadowgraphs, and the possible solutions. First of all, of course, is a means of combining film speed and light to produce sufficient exposure in a very short time. Sufficient implies that the resulting photographs will be readable even after much enlargement. Secondly, the combination must not produce interference such as shadows or an uneven density over the photograph. Thirdly, the light source must be of the right shape

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and/or size for the optical result desired. An additional requirement on the light source may be the nature of the spectrum desired. This last, in general, is not a dominant consideration. The first three are essential. In a particular problem there may be other special requirements imposed on the technique. Most of these will not be considered here.

The first requirement stated in the foregoing paragraph is the heart of the problem. As the time of the exposure gets shorter and shorter, it is obvious that either more light must reach the film, or that the film must become faster, that is, react to less light. Thus, there are basically two approaches. Considering the second approach for a moment, it can be said that advances are being made all the time in the sensitivity of film. But it is also true that unless some radical advance is made in the photographic process, such an approach shows no promise of providing more than a small part of the solution.

The other approach, then, is to raise the intensity of the incident light and to control the time it impinges on the film. This approach also offers two possible solutions. The first is to produce steady high intensity lighting and control its incidence on the film with a shutter. There are distinct advantages to such a solution, and it is under considerable study, largely in the direction of the Kerr cell. The Kerr cell is a liquid shutter whose transmission of light is controlled by the voltage impressed across it. It has been used

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successfully in a number of experiments of a specialized nature. However, in its best present development it transmits about 45 percent of the total light when open. When shut, the cell still transmits some five percent of the total light. In addition there may be some optical distortion of small magnitude adversely affecting any photograph. A recent article by Zarem describes developments in this field.(22)

The other solution, which is the subject of this paper, is the production of a high-intensity light pulse of short duration. This, at the moment, appears to be the simplest. It has been used in more or less elementary forms for a number of years, but only recently has considerable effort been made toward refinement. Sparks of relatively low intensities and of relatively long durations have been used previously in ballistic studies. Now it is desired to get very high intensities and time durations of fractions of micro-seconds. One example will suffice. Suppose an investigation is being made of atomization in an air stream at a Mach number of two. Suppose also, that the effective duration of the light pulse from a spark gap is one micro-second in length. In one micro-second a particle travels .026 inches. On the average shadowgraph this would be a relatively short distance. If the atomized drop were .001 inches in diameter and we enlarge the shadowgraph one hundred times, the drop appears .1 inches in length, while the streak actually seen is 2.6 inches long.

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This presentation might, if there were not too many drops, show the flow. But it shows nothing about the shape of the drop, and if there were many drops, the streaks would probably cross and recross to cause confusion. Such a light pulse is obviously not satisfactory in this case.

It will be noted that the phrase "effective duration" is used. "Effective duration" due to film characteristics may or may not be substantially the same as the picture of the time intensity function presented on the oscilloscope. The reasons for this will be discussed in detail later.

This paper is largely devoted to a report on an extensive investigation of short duration spark sources, but it will include some survey on other types of sources, namely flashlamps and lamps adapted for flashing. These, in general, have not been subject to the same sort of investigation, although they are a little easier to handle and use in some respects.

For a number of applications line sources are desired. For example, it is now proposed to investigate the boundary layer in supersonic flow using an interferometer, which would require a line source. In another case, for Schlieren optics, sources of finite shape and size (as distinguished from the spark which is almost a point source) are preferred. As will be shown, this is not practical with the spark, but may be almost attained with some of the others.

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The use desired will primarily determine the choice of source. The use is a combination of so many variables that to suggest all of them is impossible. A repetitive pulse may be desired. Light for still photography of a projectile in flight may be desired. Basically, however, many of these are matters of design of power supplies and triggering. The prime difficulty in design and application at present is the lack of information about the fundemental characteristics of the light pulses to be obtained from the various sources under short duration high output conditions.

The following chapters attempt to describe in detail some of the characteristics referred to above with the intention of arriving at some general conclusions on which designs may be based. The author does not claim that his conclusions are necessarily definitive or final. For that reason a great deal of data is presented which another may be able to interpret differently and adapt to any number of conditions. In any case the information presented may serve as a guide in approaching a problem of this nature.

Table I illustrates the levels of intensity of the sources with which this paper deals.

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TABLE I

COMMON LIGHT SOURCES

Source	cp/mm^2
* Tungsten Lamps (house use)	.022 to .046
* Acetylene flame	.067
* Mercury arc	.93 to 1.55
* Tungsten filament (gas filled) (10 lumens per watt)	4.69
* Tungsten filament (900 watt movie lamp)	26.6
* Tungsten filament (10 kilo-watt lamp)	30.5
* Sun at earth's surface (calculated)	1650.
* Carbon arc crater	1425.
* Blackbody at 5000° K	840
Liebessart Gap (10,000 volts)	1854×10^3
AH-6 (Mercury tube used as flashlamp)	3×10^3
FT-121 (Flashlamp)	4×10^3

* (First part of Table from: Light Photometry and Illuminating Engineering, by W. E. Barrows, McGraw-Hill, Inc.)

Last three sources are short duration source values of intrinsic brilliance obtained experimentally.

CHAPTER I

THE LIEBESSART GAP

There are numbers of sources which can, or conceivably could provide short duration high-intensity light pulses. However, this investigation was originally undertaken primarily from the point of view of making shadowgraphs in wind tunnels. For this purpose the spark gap is the most widely used.

The type of spark gap investigated here is of a rather special nature. Known as the Liebessart gap, it was introduced in this country by General (then Colonel) Paul Liebessart of the French Army who suggested it to the Ballistics Research Laboratories at Aberdeen. Presumably he was acquainted with some of the properties of this gap, but exactly how much is not known in this country. Certainly the information available to the above institution was not extensive. The Liebessart gap is an enclosed gap in air as illustrated in Figure I.

It is essentially a pressurized gap. The insulator enclosing the gap is of a glass bonded mica known as "Pem-Que". Soapstone has been successfully used as have other similar materials. Many fairly hard materials with a high arc resistance and good insulating qualities can be used.

The light output from this gap is from three to ten times (depending on input) that of the plain open gap.

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The electrodes in this case were made of steel. The front electrode is a threaded cylinder with a tapered hole through its axis. The outer end is cut off square. The inner end is coned to fit into a similar cone in the insulator. The rear electrode is a smaller solid cylinder which fits in a hole drilled to its size in the insulator. Both electrodes are mounted in lucite.

The investigation of this gap was undertaken in two distinct parts. The intention of the first part was to find the characteristics when used for single discharges. The object of the second part was to discover the characteristics of the spark when a repetitive pulse of a known shape was applied. As such, the power supplies and methods used were different and will be discussed separately.

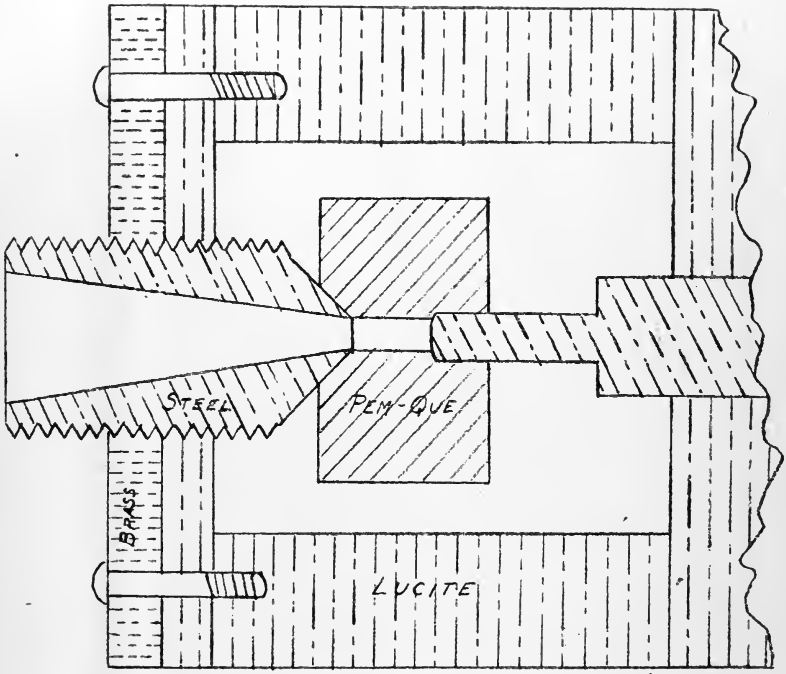


FIGURE 1

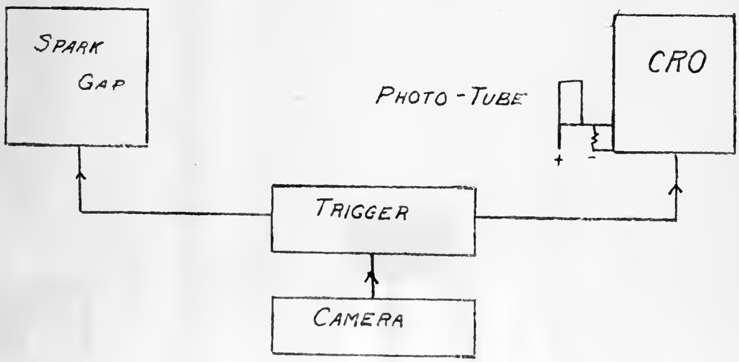


FIGURE 2

CHAPTER II

SINGLE PULSE CONDITION

2.1- Apparatus

The arrangement of apparatus is shown in Figure 2 as a block diagram. The power supply is shown in Figure 3. The particular details of the construction will be found in reference (1) which contains a description written by B. S. Melton of the Applied Physics Laboratory.

The entire assembly was triggered by a strobotac trigger which was originally built for photographic use. It was designed to produce two output pulses with a variable delay between them. However, due to coupling and insufficient shielding, only a fixed delay resulted. This delay was sufficient to make it possible to observe the whole trace.

The firing of the gap actually resulted from the triggering of an auxiliary gap arranged as shown in Figure 4. The operation of this gap results from a distortion of the lines of the field when about five kilo-volts is applied to the middle electrode (C). This must be sharply peaked pulse to get reliable firing. As can be seen, the leak-off resistor of .5 meg-ohms allows electrode (A) to come to the potential of the high voltage end. Electrode (B) is at ground potential. On distortion of the field by a negative potential, a discharge takes place. This is not a full bodied

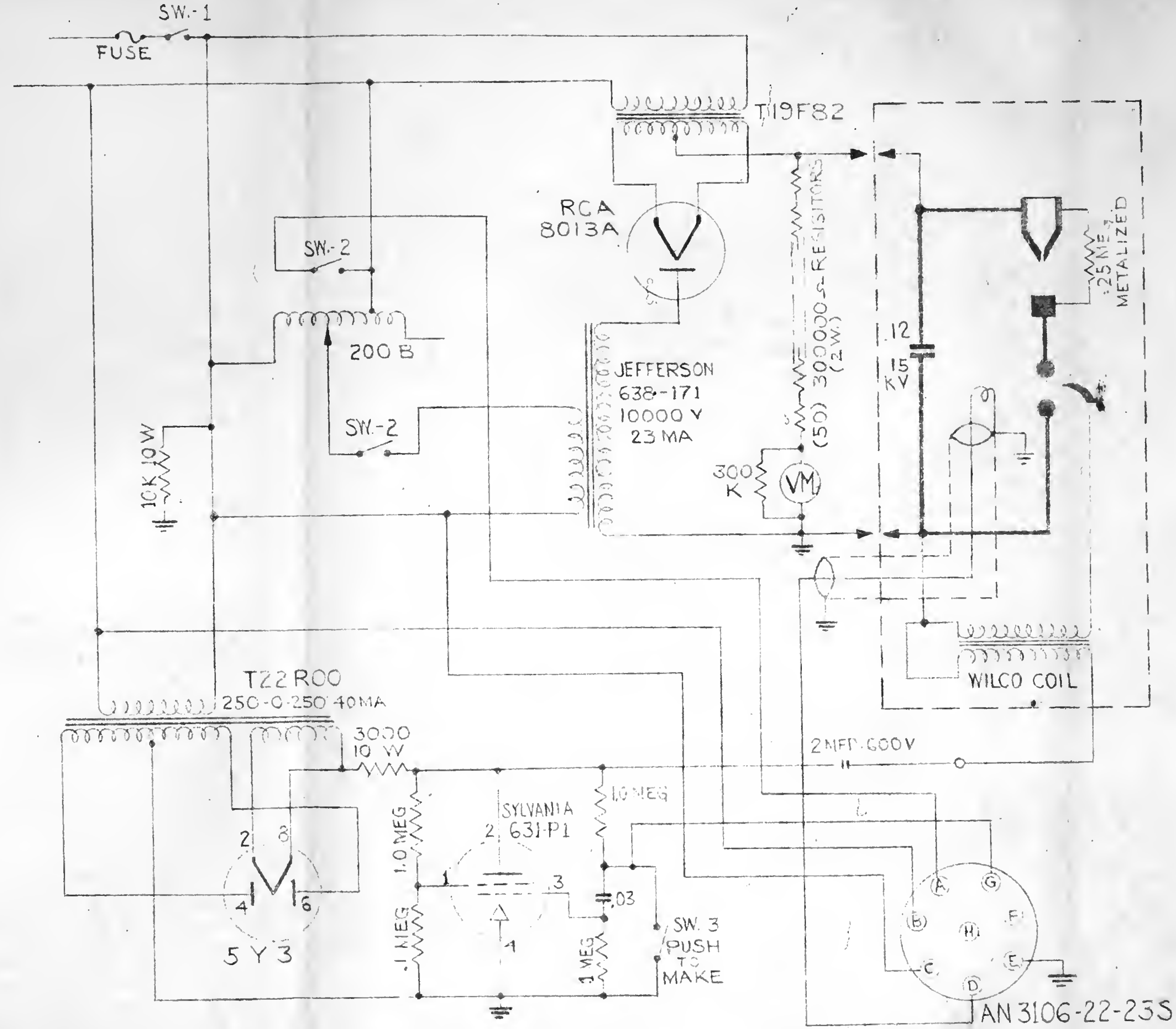
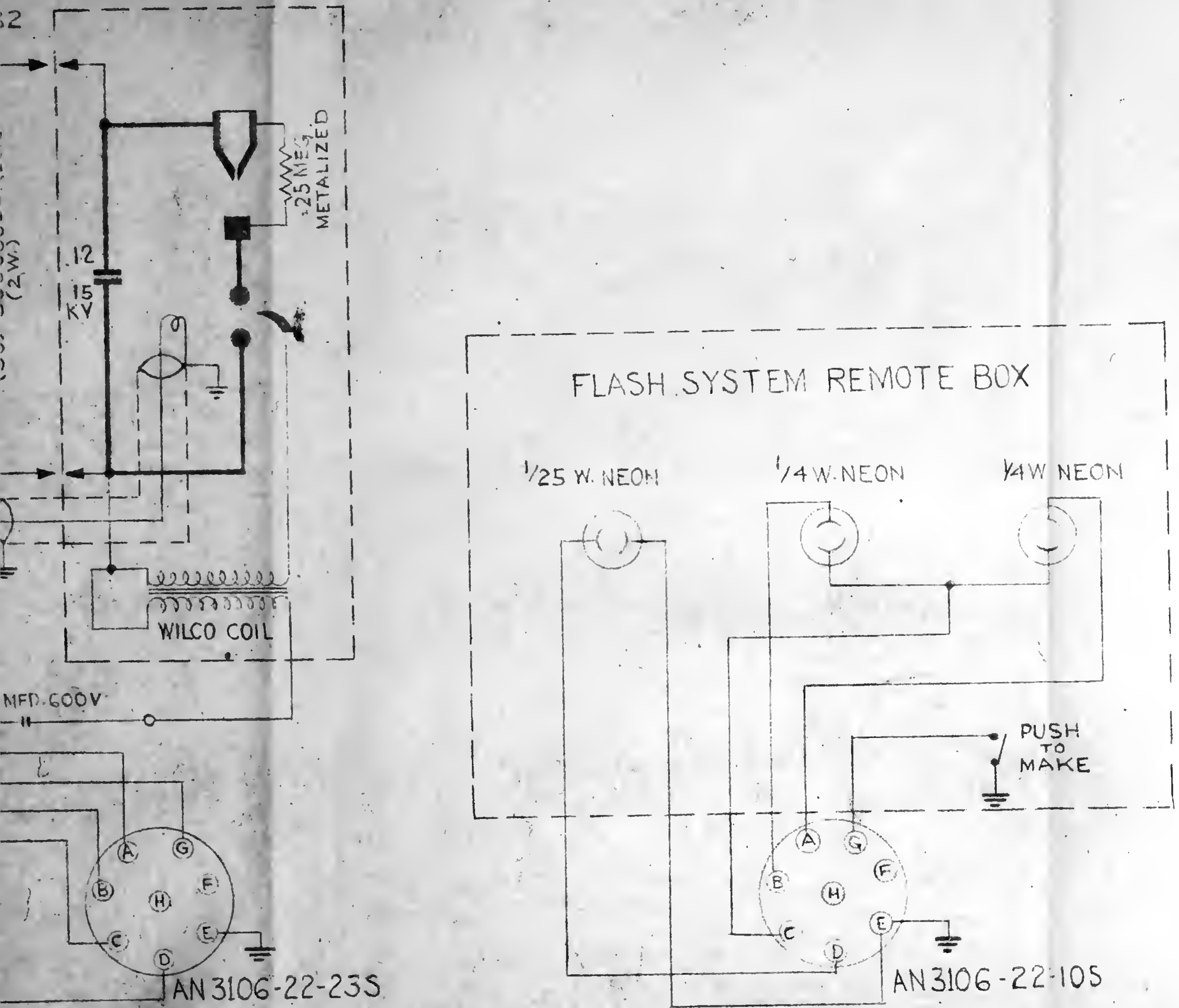

SW.-1
FUSE
T 19F82
RCA
8013A
SW.-2
200 B
SW.-2
10K 10W
JEFFERSON
638-171
10000 V
23 MA
(50) 30000 Ω RESISTORS (2 W.)
300 K
VM
.12
15 KV
.25 MEG METALIZED
WILCO COIL
T22 R00
250-0-250 40 MA
3000
10 W
2 MFD. 600 V
1.0 MEG
SYLVANIA
631-P1
1.0 MEG
.1 MEG
.03
.1 MEG
SW. 3
PUSH TO MAKE
5 Y 3
A
B
C
D
E
F
G
H
AN 3106-22-23S

FIGURE 3



REV.	REV. NO.	DATE	BY	CHECKED

HIGH VOLTAGE SPARK LIGHT SOURCE
SPARK GAP & TRIGGER SYSTEM
SCHEMATIC

THE KELLEX CORP. — J.H.U.
APPLIED PHYSICS LABORATORY

APPROVED [illegible] DATE 7/7/48

REVISION	DATE	BY	SCALE NONE
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AUXILIARY GAP ARRANGEMENT

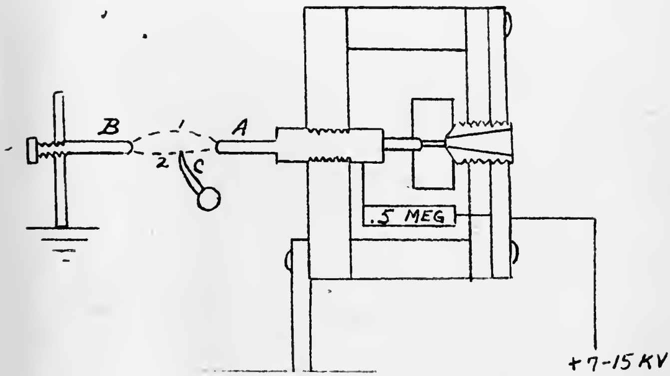

FIGURE 4

discharge at first. It may pursue path (1) or path (1) and (2); never (2) alone (this from observation). Path (2) alone is never followed because electrode (C) is negative, and a streamer cannot start from this negative point. Paths may form from electrodes (B) and (A) to (C) and then become a path from (B) to (A) because of high conductivity already established. Electrode (A) drops rapidly to practically ground potential, and the stress is applied across the main gap producing the main discharge. The exact physical explanation of the operation of this auxiliary gap is difficult. It was determined experimentally that the length of the auxiliary gap may vary over a considerable range without measurable effect on the main discharge. The upper limit of this range is determined by the point at which the gap will not fire and the lower limit by the point at which both will fire by "spill-over".

There are a number of reasons for using an auxiliary gap for firing instead of a thyratron. Chief among these is that a thyratron for the current levels we wish to use is difficult to find. In addition it introduces considerable resistance in the circuit reducing the current and the light output. The necessary wiring introduces undesirable inductance. By using an auxiliary gap, the random firing lag effect normally associated with a spark, is reduced to less than one micro-second. This is sufficient for most purposes.

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The oscilloscope used was a Dumont 248-A with accelerating potential adjustable to 10,000 volts. The amplifier has a flat response characteristic to five megacycles and the half power point occurs at about eight megacycles. This scope has a very high writing speed which is essential for this type of operation. It has an internal timing circuit which produces one, five, or ten micro-second markers. Both the characteristics and the timing markers were checked on the scope used and verified to within a few percent.

Three separate photo-cell units were used to observe the light pulse. These were a 925, 929, and a 931-A. The first two are high vacuum photo-cell units. The third is a photo-multiplier. The photo-multiplier was used with 1250 volts applied to the anode and 1250 volts between stages. The spectral sensitivity curves for the 929 tube and the 931-A photo-multiplier are the same. This curve as well as the curve for the 925 tube are shown as Figures 5 and 6.

In order for the results of these experiments to be valid, something about the frequency response of photo-cells must be known. A number of tests (reference 9) have shown that there is no apparent variation due to frequency response in a photo-cell for pulses down to 10^{-9} seconds. The capacitance of these photo-tubes is a few micro-micro-farads. The load resistances used were so low as to make the time constants negligible.

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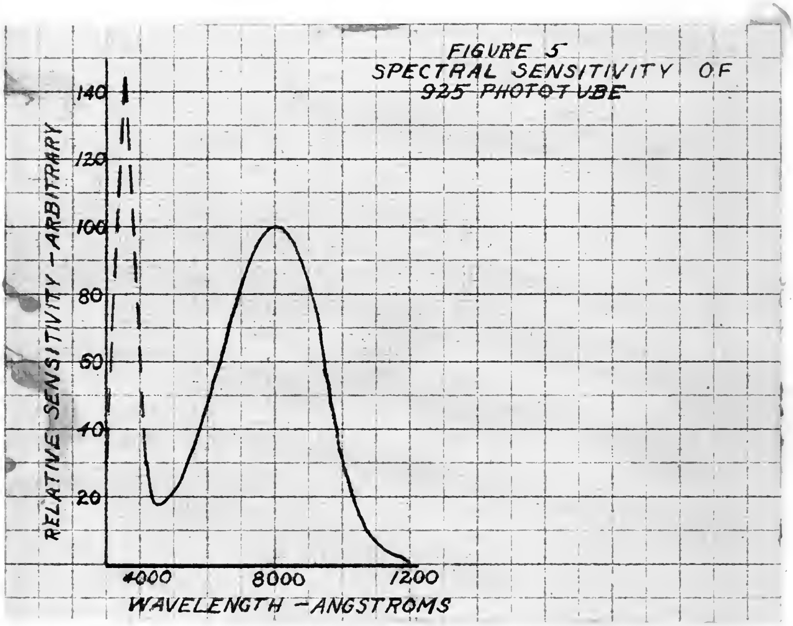

FIGURE 5
SPECTRAL SENSITIVITY OF
925 PHOTOTUBE

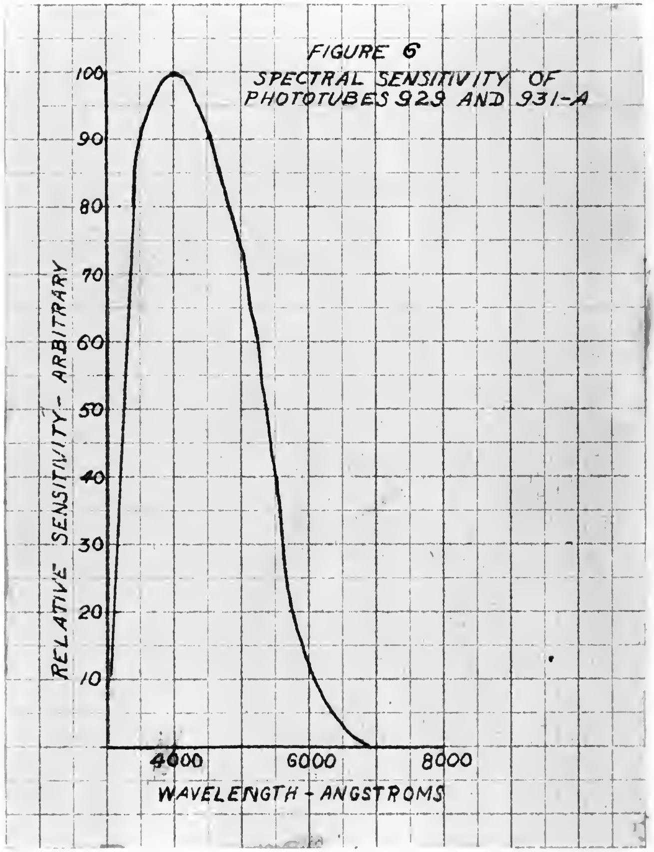
FIGURE 6
SPECTRAL SENSITIVITY OF
PHOTOTUBES 929 AND 931-A
RELATIVE SENSITIVITY - ARBITRARY
100
90
80
70
60
50
40
30
20
10
4000
6000
8000
WAVELENGTH - ANGSTROMS

ation was that the intensities were so high as to permit the use of only 500 ohms as a load on the high vacuum photo-cells with only a 45 volt potential applied. By using some amplification, even with high accelerating voltages on the cathode ray tube, the signals produced were excellent. In addition to reducing time constants, this low load and potential obviated any cable and reduced the field pickup to negligible levels. A banana plug was soldered onto the pin which connects to the photo-cell cathode. A lead to the battery was soldered on the lead to the anode; the resistor was placed directly across the oscilloscope terminals; and the negative lead from the battery was connected to the ground. The leads were short, about one inch. A picture of this arrangement is shown in Figure 7. A small shield blackened inside with a non-reflecting paint was used to shield the photo-cell from reflected pick-up.

In the case of the photo-multiplier, resistances on the order of 200-500 ohms were used. Due to saturation, the photo-multiplier was found not to be of much use in this particular part of the study. Because of the high intensities involved, and the saturation produced, two courses were open in using the photo-multiplier. One was to move the cell to a greater distance. This was physically impossible since the space was not available. The other was to interpose some filter such as ground glass. This intro-

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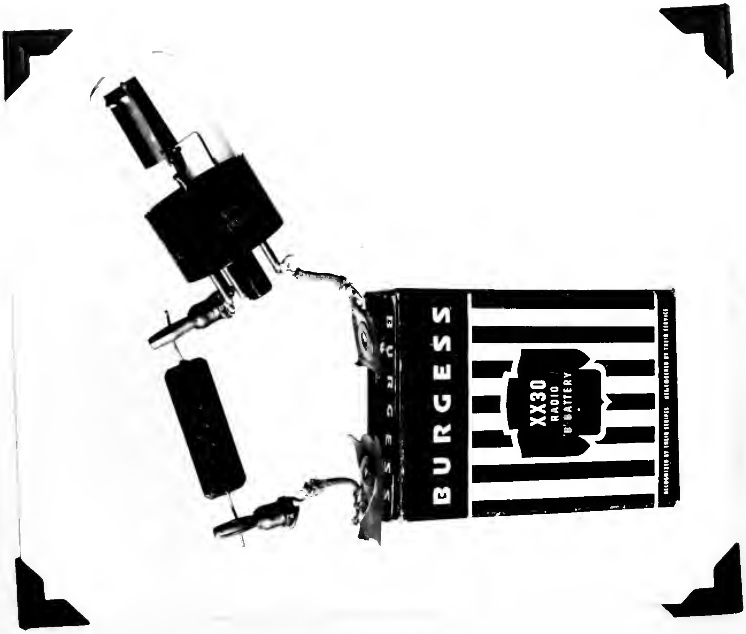


Figure 7

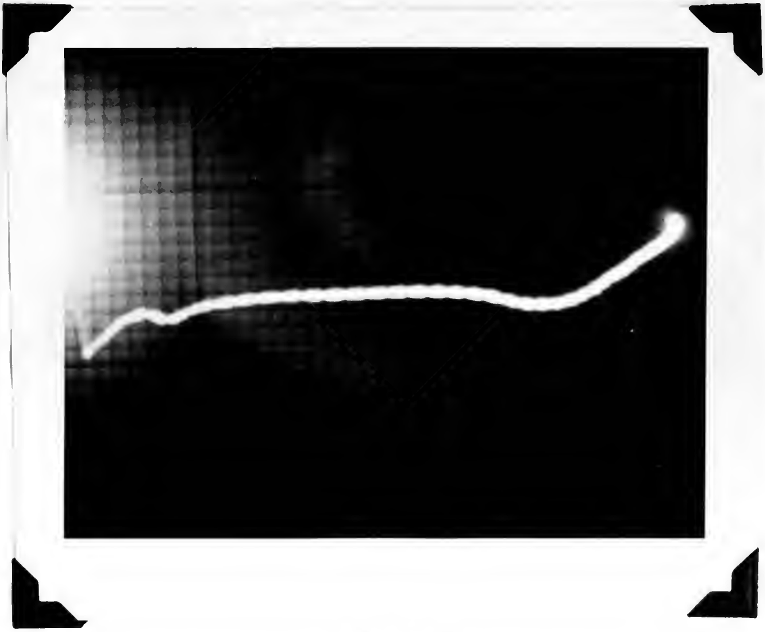
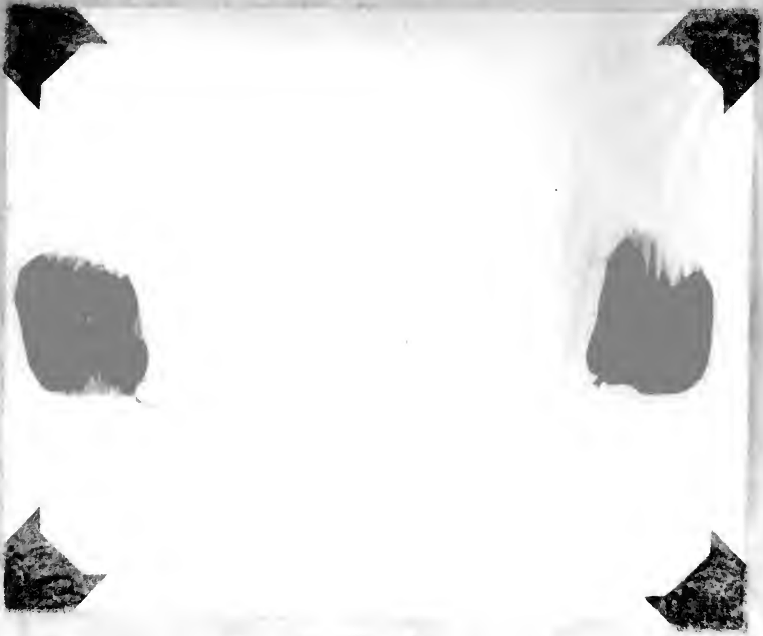


Figure 8

Figure 7



duced certain optical problems in dispersion, reflection, and absorption which it was thought better to avoid. Purely, as a rough check, the time-intensity function using a filter arrangement was recorded for a few conditions and found to be identical with the results to be discussed later.

In the use of photo-cells, great care must be taken to avoid saturation. Such saturation produces a more or less flat-topped wave followed by a decaying exponential which effectively blanks the true light pulse. Figure 8 is an example of saturation in a photo-multiplier. For contrast an unsaturated light pulse is shown in Figure 12. Probably the quickest and simplest way to check on the occurrence of saturation is to move the photo-cell away from the light source till the magnitude of the output- the light source remaining constant- begins to vary as the inverse square of the distance. Of course, with an optical system interposed this is not possible, but in cases not involving an optical system it provides a reliable check.

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ed, and the damping. There are, of course, numerous other parameters such as the composition of the air, humidity, temperature, atmospheric pressure, and possibly others. These were not controllable, but over the period of these tests they did not vary widely, certainly not outside the limits of accuracy of the experiments, since a number of these were later duplicated to assure that they were reproducible.

Among the illustrations is a spectrum of the Liebessart spark- Figure 9, (taken by E. L. Gayhart). A Wratten 18-A filter was used with the 929 cell to get mainly blue regions. A composite plot of their sensitivity is shown as Figure 10. An Eastman F filter was used to obtain mainly red regions (probably the strong line near 6000 angstroms). This filter was used in conjunction with the 925 tube. A composite plot of their characteristics is shown in Figure 11. In this connection using the 18-A Filter with the 925 photo-cell reduced the light pick-up by that cell to a level below measurement. The same was true for a combination of the F filter and the 929 tube. This justifies the conclusion that little or no blue was picked up when using the D filter on the 925 cell, and little or no red when using the 18-A filter on the 929 tube. Since the measurement of the transmission qualities of filters is not very precise, no attempt was made to get the relative intensities of the various wavelengths.

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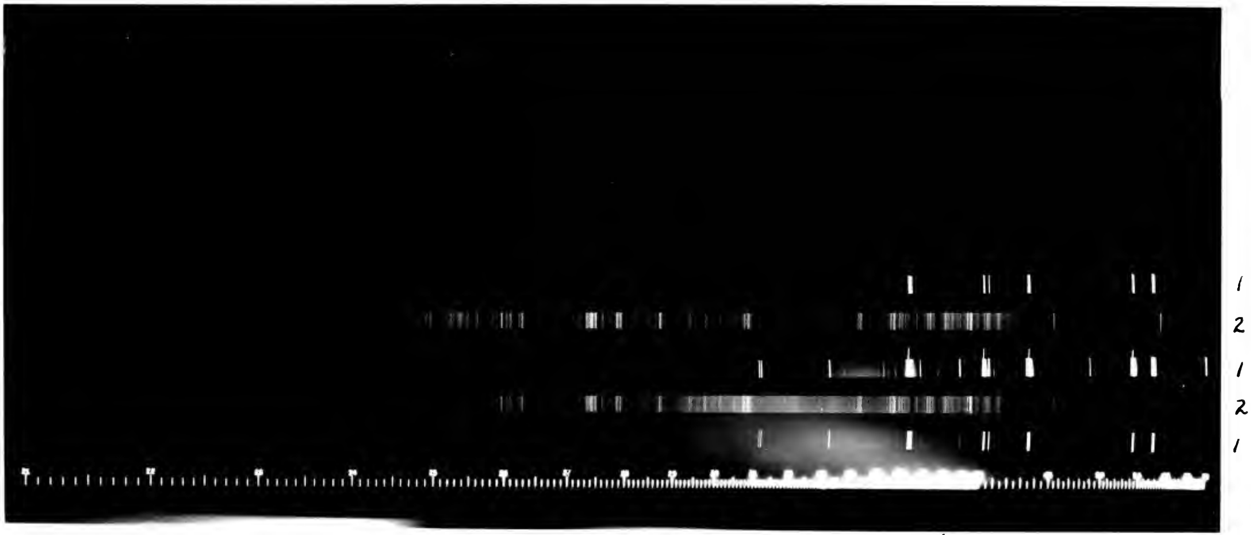


FIGURE 9

(COURTESY E. L. GAYHART APL)
1 SPARK SPECTRUM
2 IRON SPECTRUM

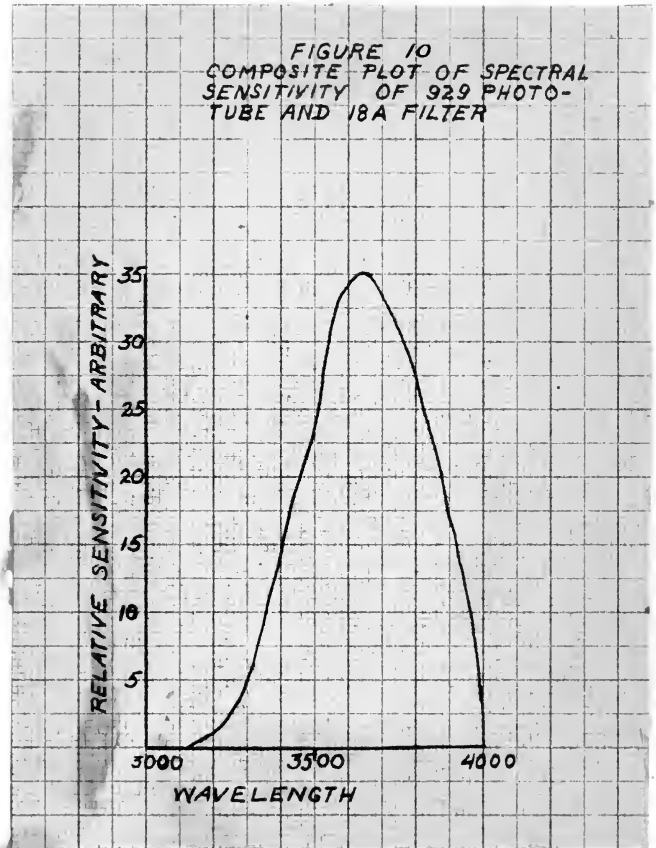
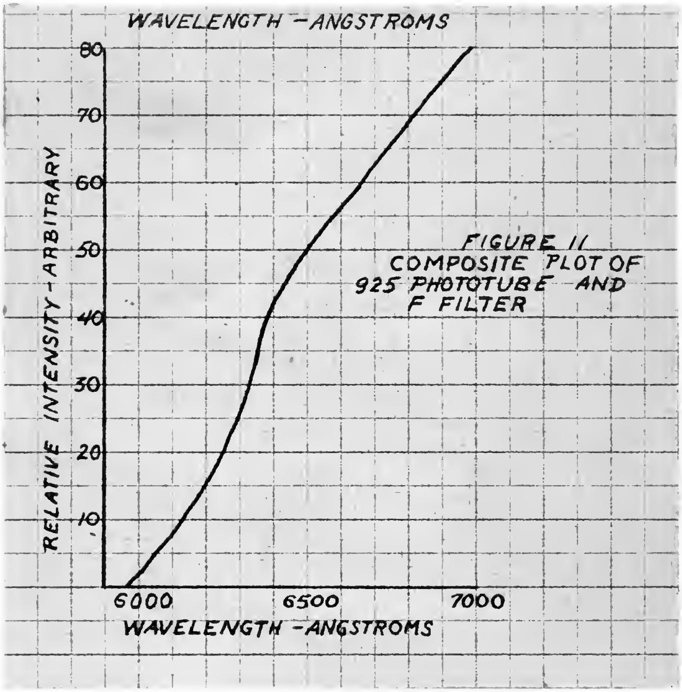


FIGURE 10
COMPOSITE PLOT OF SPECTRAL SENSITIVITY OF 929 PHOTO-TUBE AND 18A FILTER
RELATIVE SENSITIVITY - ARBITRARY
35
30
25
20
15
10
5
3000
3500
4000
WAVELENGTH


WAVELENGTH -ANGSTROMS
80
70
60
50
40
30
20
10
RELATIVE INTENSITY - ARBITRARY
6000
6500
7000
WAVELENGTH -ANGSTROMS
FIGURE 11
COMPOSITE PLOT OF
925 PHOTOTUBE AND
F FILTER

It will be noted that there is a strong line at about 4380 angstroms. A diffraction filter was used in combination with the 929 tube to obtain the time-intensity of this single line.

All the data were derived from photographs of the oscilloscope traces. The photographing of the oscilloscope trace was in itself a considerable problem. A special sliding shutter was built to initiate the triggering and expose the film at the same time.

2.3 Test Results

The test results are presented in a number of cases by graphs or charts. Certain of the results are not possible of presentation as curves and are therefore presented as oscillograph pictures. The results described below will be discussed in detail later.

Figure 12 represents the time function of the total radiation as received by the 929 photo-cell (without filters), and presented on a time base. The blanking markers shown are at one micro-second intervals. The maxima and minima correspond to maxima and minima of the current. As was determined roughly in this experiment and more exactly in a later experiment, the corresponding maxima of the light pulse lag the current maxima by about .2 micro-seconds. This lag time was also determined by Fischer and Regen (2), although more exactly. No extra damping was used in this circuit.

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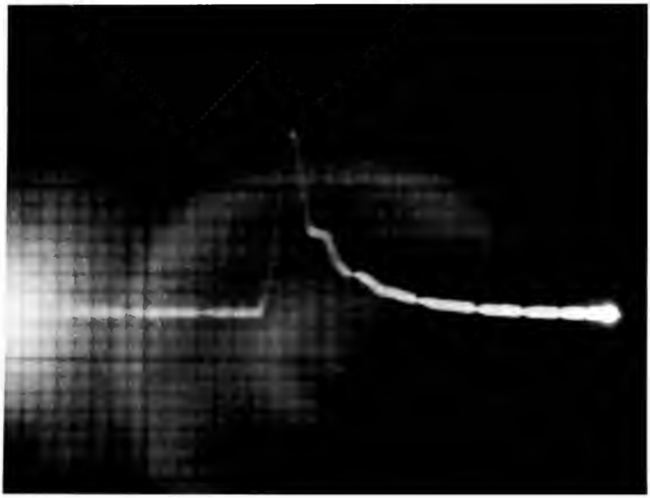


Figure 12

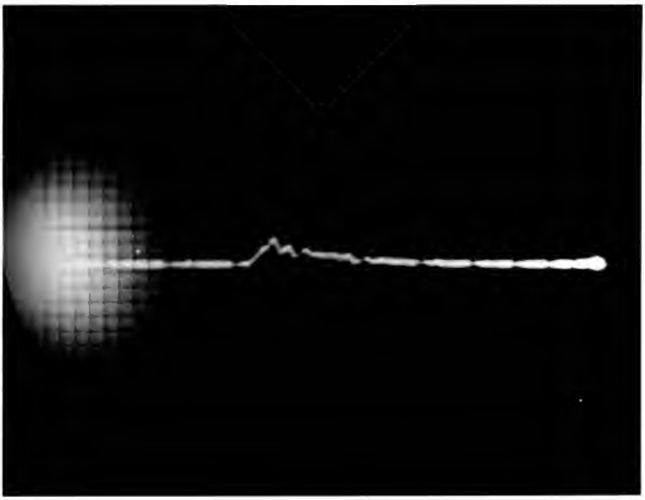


Figure 13

Figure 12

Figure 13

Figure 13 is an oscillograph picture of the time function of the light pulse filtered to get only the strong line at 4380 angstroms mentioned previously.

Figure 14 is an oscillograph picture of the time function of the red regions. Figure 15 represents the trace of the light pulse for the blue regions.

Figure 16 represents a picture under the same conditions as Figure 12 but with .42 ohm added damping inserted in the circuit.

Figure 17 represents a plot of the maximum relative intensity reached (as received by the 929 photo-tube) versus the voltage on the condenser on firing. It will be noted that the slope varies about as E to the 1.2 power.

Figure 18 is a plot of the maximum relative intensity reached versus volume of the enclosed gap.

Figure 19 is a plot of the maximum intensity reached versus length of gap. Dotted portions represent the region in which data was scanty or unobtainable. Figure 20 is the maximum relative intensity plotted versus diameter of gap.

Figures 21, 22 and 23 are plots of the decay of the radiation versus time in various regions. Figure 24 is a plot of the decay with increased damping.

Figure 25 represents the reduction in maximum total radiation due to damping inserted in the circuit. Figure 26 is a typical current oscillogram. Due to certain

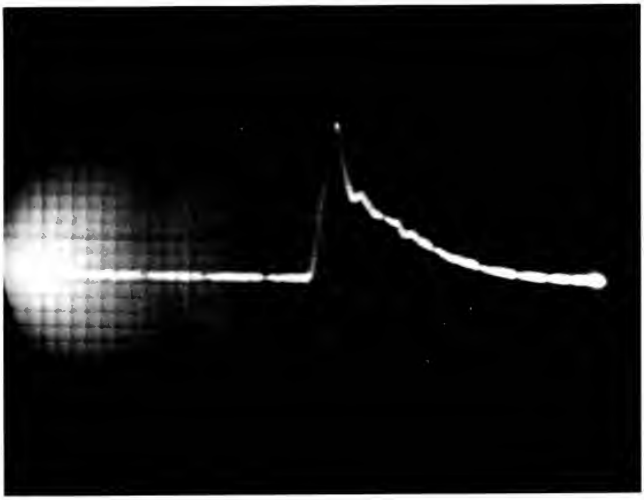


Figure 14

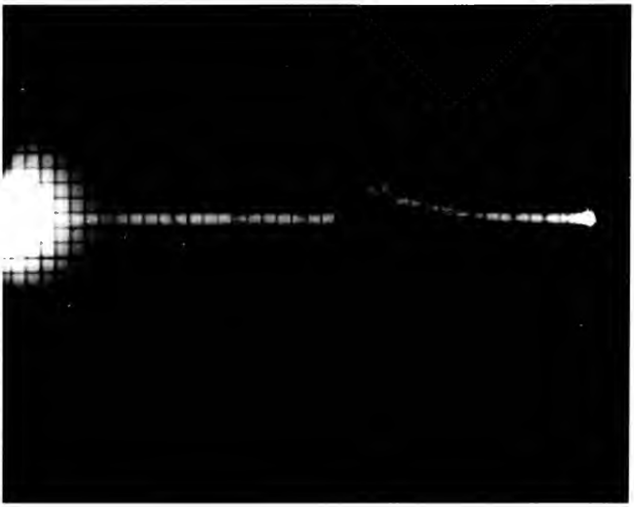


Figure 15

Figure 14

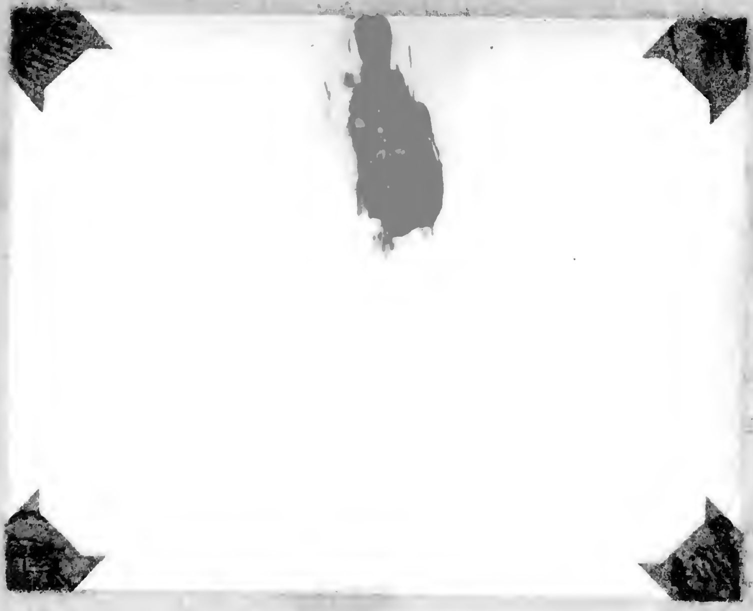


Figure 15

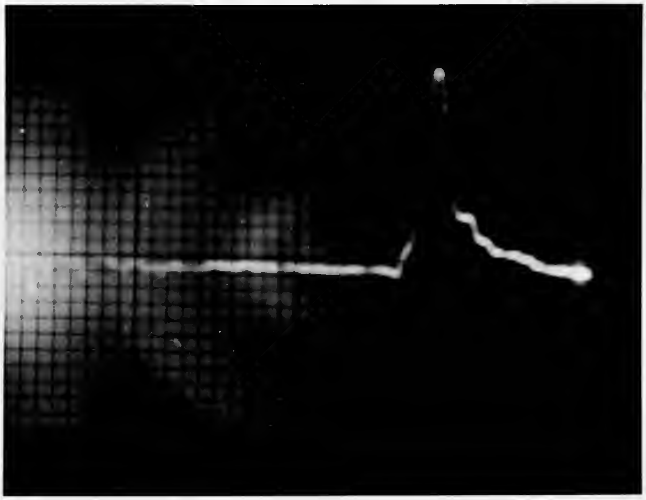


Figure 16

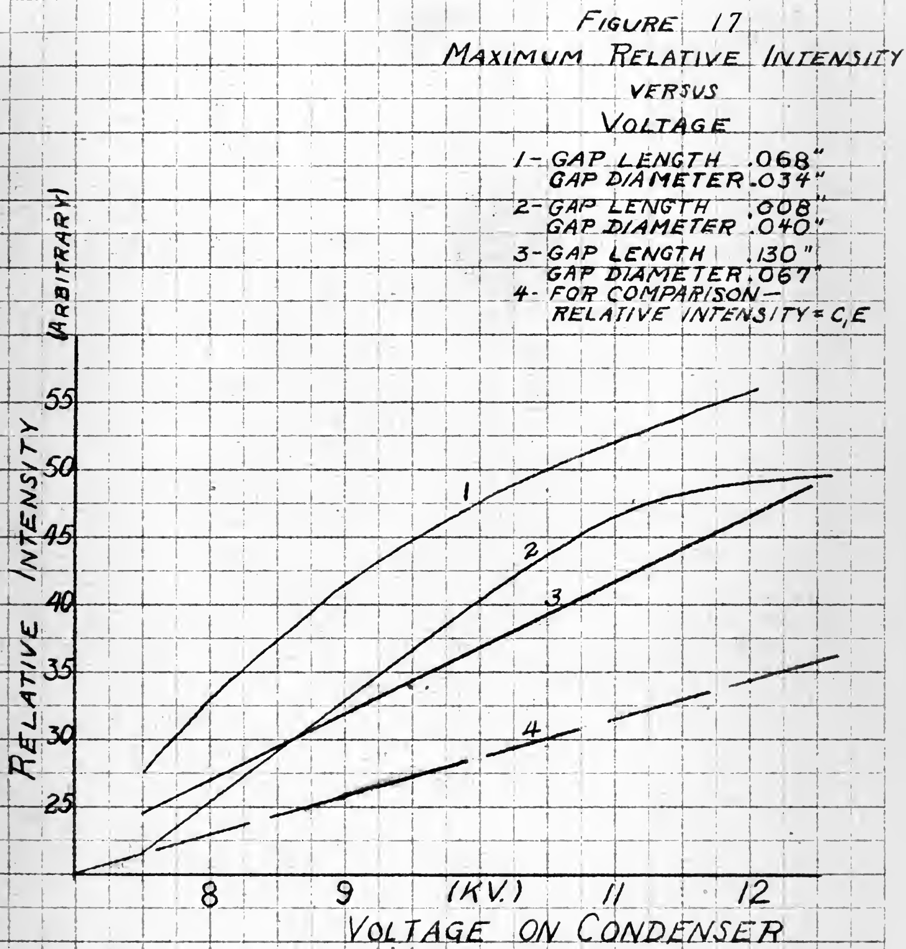


FIGURE 17
MAXIMUM RELATIVE INTENSITY
VERSUS
VOLTAGE
1- GAP LENGTH .068"
GAP DIAMETER .034"
2- GAP LENGTH .008"
GAP DIAMETER .040"
3- GAP LENGTH .130"
GAP DIAMETER .067"
4- FOR COMPARISON—
RELATIVE INTENSITY = C,E
RELATIVE INTENSITY (ARBITRARY)
25
30
35
40
45
50
55
1
2
3
4
8
9
(KV.)
11
12
VOLTAGE ON CONDENSER

FIGURE 18
MAXIMUM RELATIVE INTENSITY
VERSUS
VOLUME

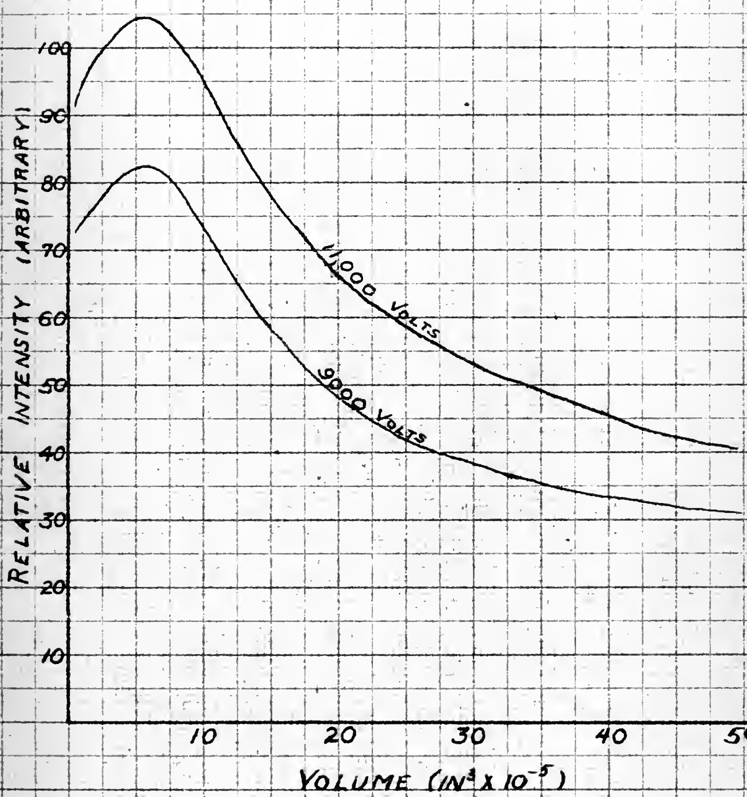
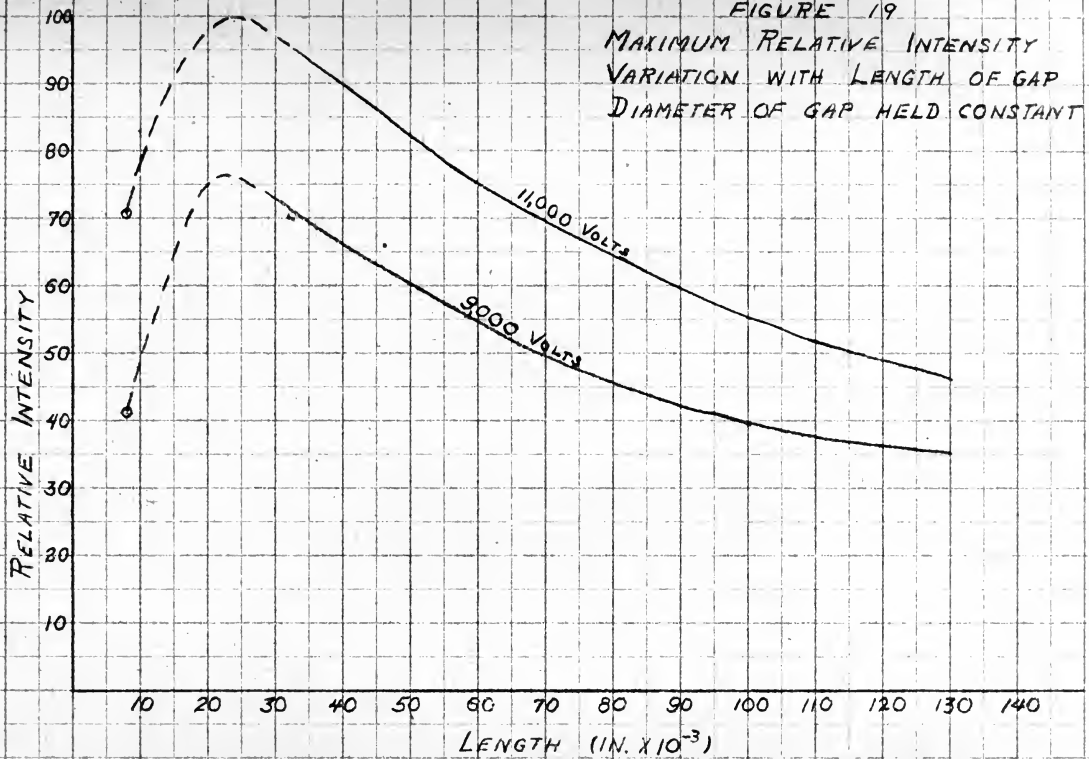


FIGURE 19

MAXIMUM RELATIVE INTENSITY
VARIATION WITH LENGTH OF GAP
DIAMETER OF GAP HELD CONSTANT (.04")



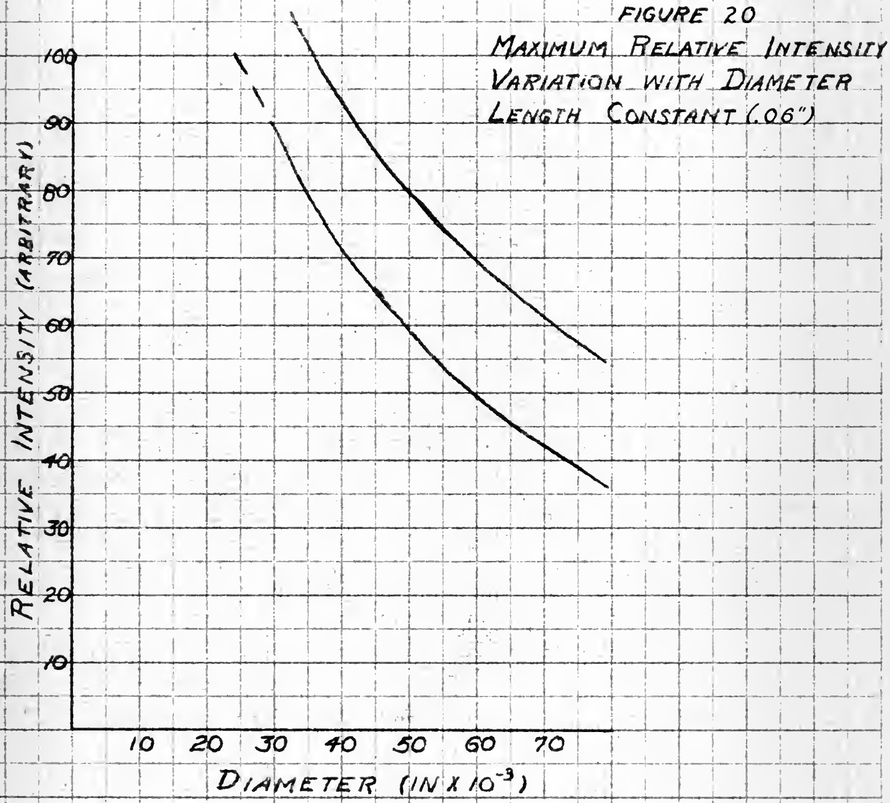


FIGURE 20
MAXIMUM RELATIVE INTENSITY
VARIATION WITH DIAMETER
LENGTH CONSTANT (.06")
RELATIVE INTENSITY (ARBITRARY)
100
90
80
70
60
50
40
30
20
10
10
20
30
40
50
60
70
DIAMETER (IN X 10^{-3})

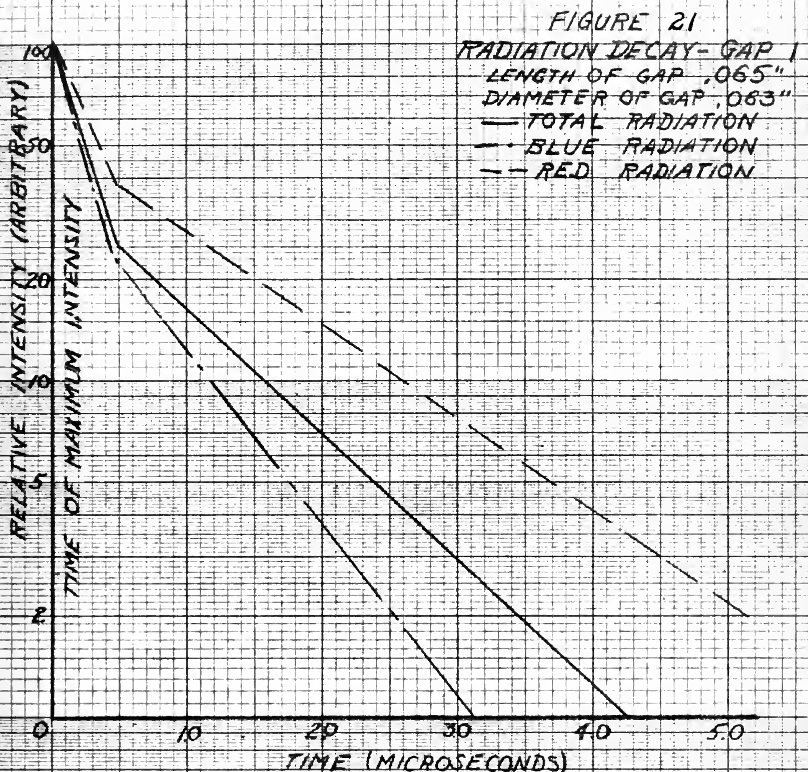


FIGURE 21
RADIATION DECAY - GAP 1
LENGTH OF GAP .065"
DIAMETER OF GAP .063"
— TOTAL RADIATION
—· BLUE RADIATION
— — RED RADIATION
RELATIVE INTENSITY (ARBITRARY)
TIME OF MAXIMUM INTENSITY
100
50
20
10
5
2
0
1.0
2.0
3.0
4.0
5.0
TIME (MICROSECONDS)

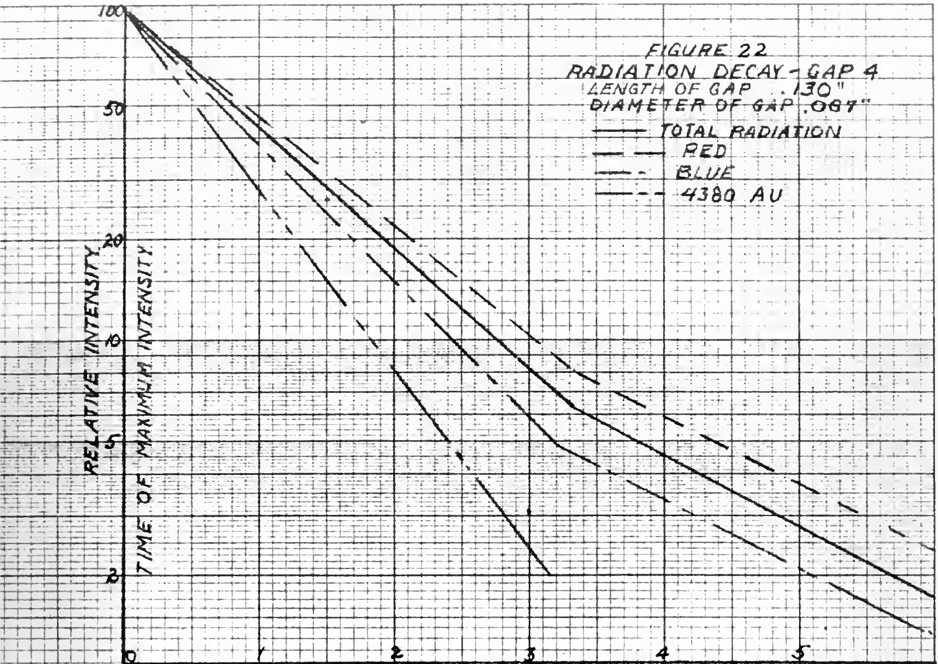


FIGURE 22
RADIATION DECAY - GAP 4
LENGTH OF GAP .130"
DIAMETER OF GAP .067"
TOTAL RADIATION
RED
BLUE
4380 AU
RELATIVE INTENSITY
TIME OF MAXIMUM INTENSITY
100
50
20
10
5
2
0
1
2
3
4
5

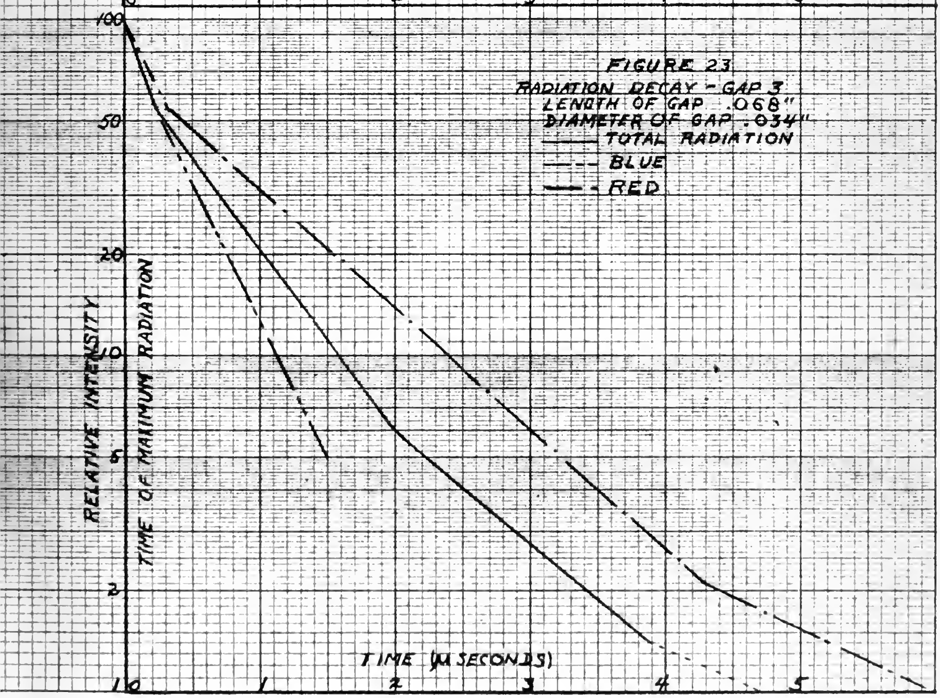


FIGURE 23
RADIATION DECAY - GAP 3
LENGTH OF GAP .068"
DIAMETER OF GAP .034"
TOTAL RADIATION
BLUE
RED
RELATIVE INTENSITY
TIME OF MAXIMUM RADIATION
TIME (μ SECONDS)
100
50
20
10
5
2
1.0
1
2
3
4
5

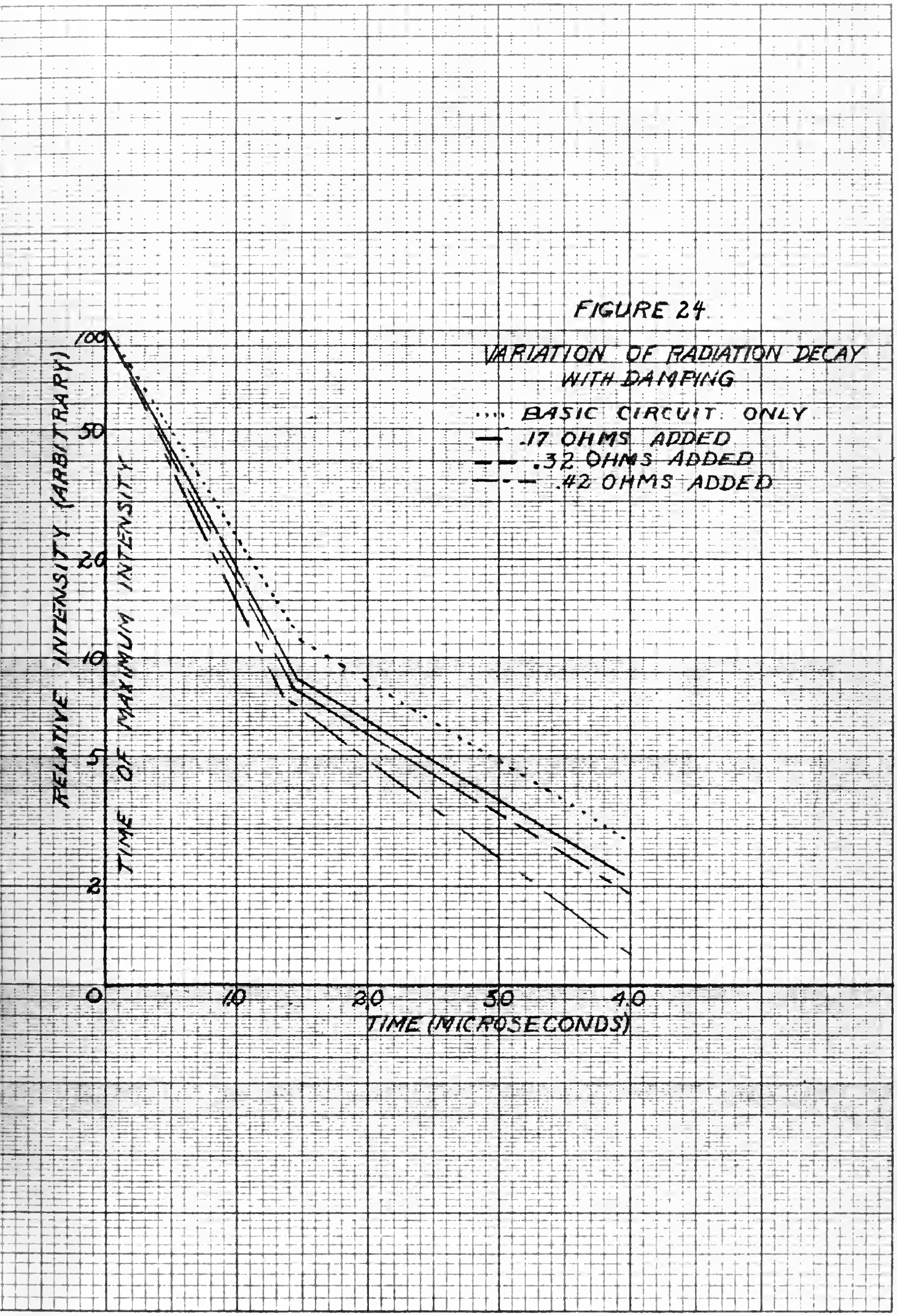


FIGURE 24
VARIATION OF RADIATION DECAY WITH DAMPING
BASIC CIRCUIT ONLY
.17 OHMS ADDED
.32 OHMS ADDED
.42 OHMS ADDED
RELATIVE INTENSITY (ARBITRARY)
TIME OF MAXIMUM INTENSITY
100
50
20
10
5
2
0
1.0
2.0
3.0
4.0
TIME (MICROSECONDS)

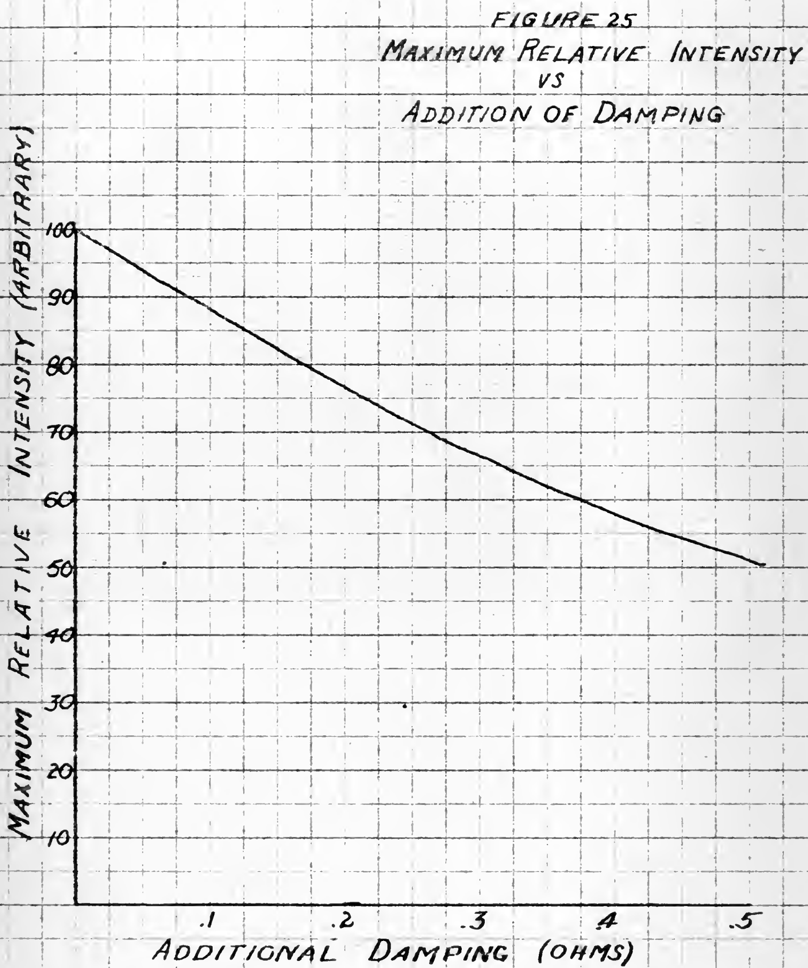


FIGURE 25
MAXIMUM RELATIVE INTENSITY
VS
ADDITION OF DAMPING
MAXIMUM RELATIVE INTENSITY (ARBITRARY)
100
90
80
70
60
50
40
30
20
10
.1
.2
.3
.4
.5
ADDITIONAL DAMPING (OHMS)

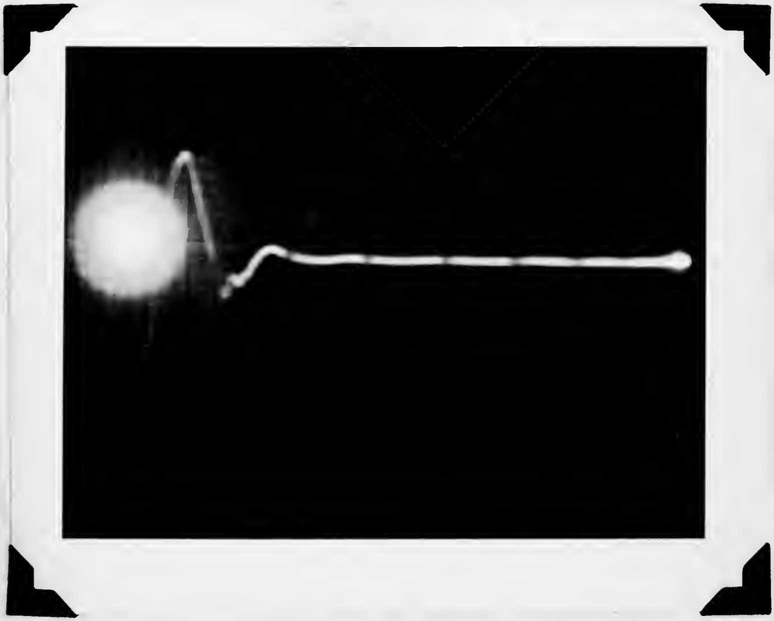


Figure 26

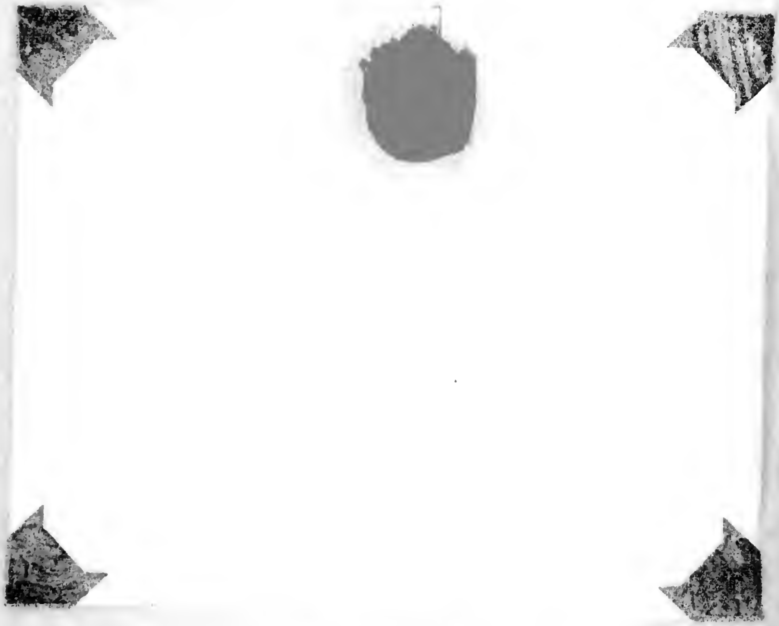


Figure 26

triggering difficulties there was no delay in firing and the initial current rise does not appear. This is a typical oscillatory discharge.

Certain assumptions were made in these results. The most important assumption is that the radiation received was inversely proportional to the square of the distance. This is a fairly good approximation for the distance involved. The second is that there was no reflected pick-up of light. This is practically assured by the precautions taken.

2.4 Discussion of Test Results

The light pulse as a whole seems a logical starting point for this discussion. As an indication of the accuracy of the result, it is interesting to compare the time intensity function obtained here with some previous data.

Some time before this experiment was begun, the Applied Physics Laboratory set up an experiment to determine the time intensity function of the light from this gap using a rotating mirror. The gap light was reflected from the rotating mirror onto a photographic plate. A microdensitometer trace was then made from the resulting exposure. The smoothed plot is shown as Figure 27.

Now if Figures 27 and 12 are compared, it will be seen that the time of the maxima and minima correspond almost exactly at least within the limits of experimental error,

[illegible] as [illegible] in Figure and the initial [illegible] not [illegible] appear. This is a typical oscillatory discharge.

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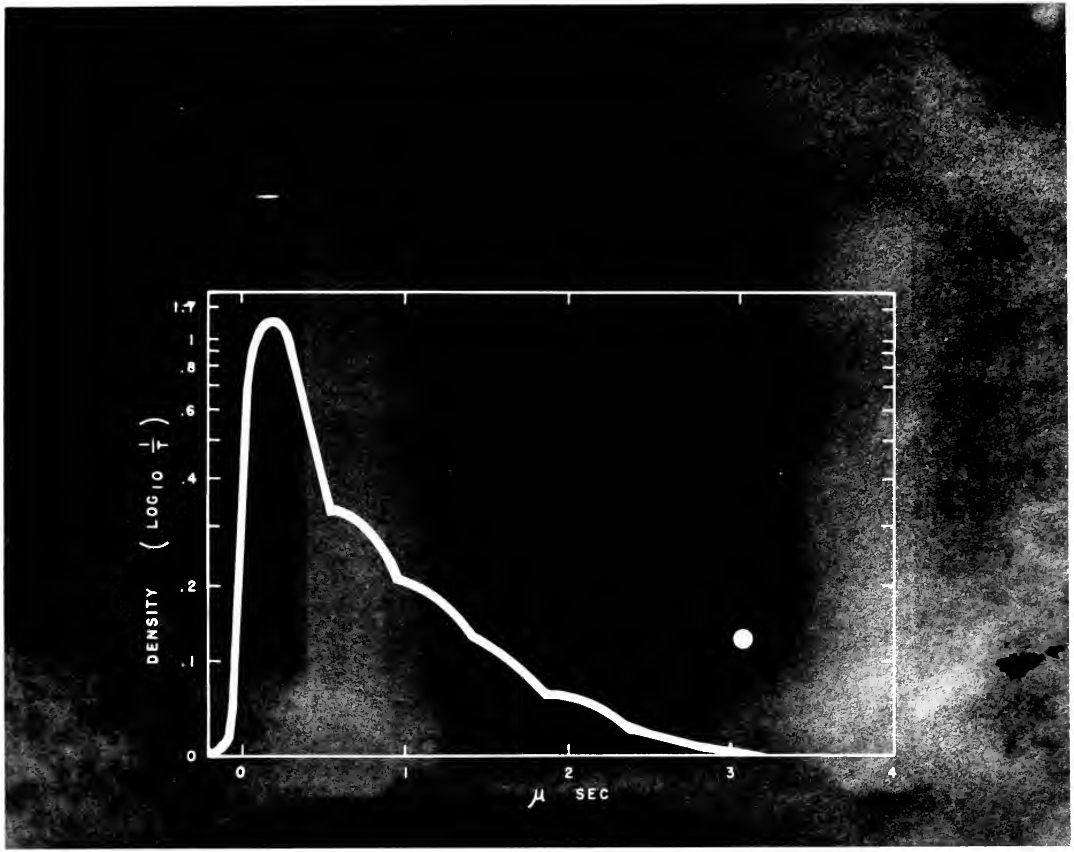
DENSITY $\left(\log_{10}\frac{1}{T}\right)$
0
.1
.2
.4
.6
.8
1
1.7
0
1
2
3
4
μ SEC

($\pm$ .05 micro - seconds). However, if the relative values of the maxima and minima are compared they do not check. This can probably be accounted for by the D Log E curve of the film. A typical D Log E curve (15) is shown in Figure 28.

Normally film operators on the straight portion of the graph in which case the density is proportional to Log E, where E is exposure. The equation, D + constant = γ Log E, expresses this. γ is the slope of the curve. Now the shape of the "gamma" curve at low exposures has not been very thoroughly investigated. It is very probable from what is known that the density at low levels is proportional to the exposure. If this is the case, exposure varies directly as intensity. This would mean then that the density level on the microdensitometer trace would be a direct function of the intensity plus a constant which would raise the whole level. If this is considered to be correct, the values compare fairly closely. It is believed any further discrepancies can be accounted for by the characteristics of the film. This behaviour of film at low levels of intensity gave rise to the earlier remark about "effective duration".

The plots show that the intensity of the Liebessart gap decreases with increasing length. This is not entirely unexpected. Although length increases the resistance

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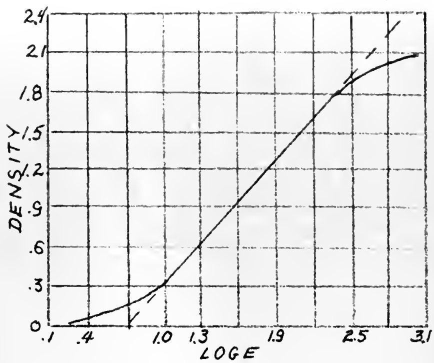

FIGURE 28
D LOG E CURVE OF A TYPICAL FILM

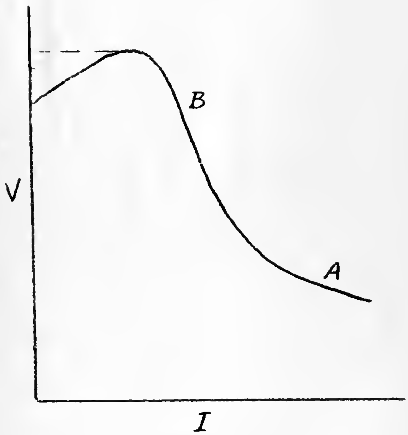

FIGURE 29
VOLT-AMPERE CHARACTERISTIC OF A SPARK

of the gap and thus the power input, the volume also increases, decreasing the energy per unit volume. Of course there is an upper limit to the length dependent on the voltage available.

Figure 20 shows that the light output increases as the diameter of the gap decreases. This is to be expected since the temperature and pressure increase with the input of energy volume. By supposition there must be a point at which a decreasing diameter produces a reduction of light due to cooling by the walls and restriction of the spark. Eventually no spark will appear at all.

Some rather important results are closely related to these effects. The decay lines were plotted for three sizes of gap, plotting blue regions, red regions, strong blues lines, and total gap output (Figures 21-23). Without exception the decay of blue is much faster than the red or total radiation. This might have been expected since blue represents short wavelengths and higher energy levels. Blue is produced by the high excitation which exists during the first part of the discharge. Red decays the most slowly of all.

Although the effects are harder to separate, in general the bigger the gap the slower the decay. This probably occurs for several reasons. First of all, assuming the same amount of energy was put into the gap in each case, the energy levels were higher in the small gap and less dependent on temperature. The temperature and energy level differ-

of the gas in the low power input, the volume also increases, decreasing the energy per unit volume. Of course there is an upper limit to the length dependent on the voltage available.

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entials between the excited matter in the gap and the walls and outer air are higher, therefore the decay is more rapid. However, beyond a certain point, the slope of the decay line for all spectral regions changes to approximately the same rate. The decay in this region, therefore, is probably a more normal rate of decay related to a certain temperature level. This may be partly due to some escape of gas from the gap and a more stable condition.

It should also be noted that the strong line (4380 angstroms) decays most rapidly of all. It is therefore a reasonable assumption that the greater the shift toward shorter wavelengths and high energy levels, the more rapid would be the decay. Furthermore, it can be seen that the total radiation line in the case of the smallest gap fairly closely follows the strong line, whereas in larger enclosures, it more nearly approaches a half-way decay between the red and blue regions. This would lead to the conclusion that the energy level was the highest in the case of the small enclosure. In turn the conclusion may be drawn that the radiation intensity per unit area will be the greatest for the small enclosure, which is the result actually obtained.

There is, seemingly, a practical limitation on this. In Figure 18 is plotted maximum light output versus volume of gap. The light increases up to nearly the smallest

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volume tried, when it drops off suddenly. Whether the volume or the configuration controlled the limit is difficult to determine. The length (.008") of the smallest gap used was very short in comparison to the diameter (.040"). The spark channel normally expands to about .06 centimeters (2). This is not a limitation here. It may be that the streamers and channel followed the walls so closely they could not expand sufficiently. Or it may be that the length was so short as to produce a very, very low resistance insufficient to get good energy transfer. If the volume were made smaller by reducing the diameter more and the length less, the light output might increase. Unfortunately, this condition was not physically attainable during this experiment so that the point remains in doubt.

The rise time of the radiation to its maximum is about .4 micro-second. It starts off at a rate which would give a rise time of .2 micro-second. This is determined, primarily, from the circuit constants. Since the frequency of oscillation of the discharge is about 1.15 megacycle (from the maxima and the minima of the light pulse and later from the current), and C is .120 micro farad, the inductance is calculated as .16 micro-henry. It is not believed possible to get very much lower inductance values than this in any practical circuit. Any gain made here is of great assistance since this will give a steeper rise. Incidentally,

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the circuit rise may or may not determine the steepness of the rise of the light pulse. This may be independent of the circuit if the rise becomes steep enough.

The forgoing statement is related to the lag observed between light maxima and current maxima by an explanation given by Fischer and Regen (2) from a report by Rompe. First of all, it must be restated that the radiation intensity lags everywhere behind the current by about .2 micro-second. This writer was inclined to attribute this to delay in some line or component when it was first noticed, but could find no such source of error. Somewhat after the effect was first noted, confirming evidence came from the aforementioned article. Although Rompe's report has not been available, the above authors state that Rompe suggests such a result. The theory advanced to account for this is outlined as follows. During breakdown, energy levels are so high that the radiation is largely short wavelength radiation which is absorbed in the boundary layer. This layer re-emits the radiation. This process is called radiation diffusion. Since it proceeds slowly, it is not till the channel has expanded and cooled that the combination of area and increasing wavelength produces appreciable radiation.

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This theory would also say as a corollary, that there must be some limit independent of the rate of rise of the

current at which no increased rate of rise of the radiation would result from a steeper rise of the current. However, it is doubtful that such a limit could be reached in practice.

It is interesting to note in Figure 13 that the maxima and minima imposed on the decay in the blue regions are much more marked than in any other spectral region. This would tend to indicate a greater sensitivity in this spectral region to slight increases of input energy. This is a reasonable result when considered in conjunction with the other results.

Figure 12, considering 50 percent of the peak as a standard, displays a time duration of about .7 micro-second. Beams and Snoddy (10) claim to have produced a non-repetitive spark of .1 micro-second duration. They designed a pulse line with such a time function to feed a shaped pulse to a spark gap. The line was operated at very low voltage and low power level. It is the writer's belief that this operation was at such a low level that only the tip of the first peak was detectable. This is further borne out by the fact that the dynamic resistance of the gap is negative and changing (as will be shown shortly). It would then be impossible to completely match the line. The actual resistance is changing and is probably on the order of .01 ohms. To get such a line would require on the order of .05 microhenry.

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This is very difficult to attain.

2.5 Damping

In order to investigate the effects of damping, various resistances were inserted in the circuit. This has the big disadvantage of reducing the power in the gap. The results in this direction may be seen from Figure 25. By extrapolating the curve of Figure 25 out to the calculated critical damping value of 2.5 ohms it can be estimated that the intensity will be only between 15 and 25 percent of the value with no damping in the circuit other than that of the condenser and necessary leads.

In calculating the resistance of the gap, there are a number of difficulties and the accuracy is not high. The surge resistance of the capacitance was taken as that calculated by Melton (4). This seems to be a valid measurement. It is very difficult to measure the surge impedance of the remainder of the circuit, but it is very low, except for inserted damping resistances. Taking all the circuit resistance as being about as much as that in the capacitance measuring circuit of (4) the basic circuit resistance is .51 ohms. Damping resistances were inserted and measurements taken. Using the following two formulae:

$$\ln \frac{I_n}{I_{n+1}} = \frac{R}{2Lf}$$

$$f = \frac{1}{2\pi}\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}$$

the inductance and resistance can be calculated. Here the frequency and the log decrement can be measured and the capacitance is known. Note that insertion of the resistances also adds inductance. The results are tabulated.

TABLE A

Added Resistance	Calculated Inductance	Calculated Damping	Gap Resistance
0 ohms	.17 microhenries	-	-
.168 "	.28 "	.626 ohms	-.052 ohms
.32 "	.39 "	.603 "	-.227 "
.418 "	.49 "	.656 "	-.272 "

If the assumption is made that the maximum light intensity is proportional to the current, and in addition that the drop in light output is due only to the added resistance, and approximate calculation can be made as a check. A series of equations may be set up as follows:

$$\frac{1}{(R_c + R_g) + R_{D1}} = KI_1$$

$$\frac{1}{(R_c + R_g) + R_{D2}} = KI_2$$

Where: I maximum intensity (light)

R_c circuit resistance (constant)

R_D damping resistance inserted

R_g gap resistance

Solving these simultaneously will give a sort of an average ($R_c + R_g$) through the region between the two measurements. From these equations the following values result.

TABLE B
(Values in Ohms)

Total R	$R_c + R_g$	Gap Resistance
.730	.605	.085
.760	.440	-.070
.786	.366	-.144

The assumptions made above are considerably more valid than might at first appear. Figure 25 represents the maximum light intensity as a function of the inserted damping. This curve very closely approximates a reciprocal curve, that is to say $I = \frac{K}{R}$.

The curve for the variation of the maximum intensity with voltage would indicate that the maximum light intensity reached is indeed a direct function of the current.

The first calculation was made on the assumption that this is an RLC circuit of constant parameters. This is undoubtedly not exactly true, but the magnitude of the variation is not known. Measurements at the lower end of the pulse are small and not too accurate. However, they indicate that there may be some change, and that the negative

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damping by the gap pr bably increases.

The curves of Loeb, Slepian, and Cobine for gaseous discharges show that a spark operates in a region of large negative slope. This is shown in Figure 29 taken from reference (17). The results of the damping would seem to show that for high currents the spark operates near point A and as current decreases the spark operates farther up the curve toward B. It should be noted that the value of the resistance for the gap as given by the first result in Table B, which result is for the highest current, compares with the values of .02 to .1 ohms given by a number of authorities and would indicate operation at a very low point on the curve. If the first maximum is considered, it may be calculated that the voltage across the gap is about 250 volts which would make the gap resistance less than .1 ohm.

From measurements made with the .168 ohms additional damping inserted, the actual peak current is taken to be about 2700 amperes. This is compared to a calculated peak current of 3400 amperes. The measurement would give an actual r.m.s. value of about 2100 amperes. If one calculates the energy input over the first quarter cycle of the discharge oscillation it may be found that approximately .7 joules is used in the resistance and that about 1.1 joules must be used in the gap. In the second quarter cycle,

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one needs to assign less than .1 joule to the gap. This it appears that most of the energy goes in during the first quarter cycle.

It must be admitted that, while every effort was made to keep the inductance in the current measuring circuit to a minimum, as a practical matter such minimum may not have been negligible. Therefore the current values quoted from measurement are open to possible inaccuracy. The proportions of the energy division in the circuit will remain the same nonetheless. Any such error in the current measurement has the effect of multiplying the given energy values by a constant.

The damping shifts the decay slope somewhat. The change in slopes occurs later in the cycle as can be seen from Figure 24. If the 10 percent level is taken as the duration, the damping decreases the duration by about 10 percent. If a higher level is taken it may equal, or even increase the time.

There is an excellent reason for damping. If the maxima and minima superimposed on the decay are of large magnitude, they produce shadows on the photograph or shadowgraph. This occurs in the following manner. Suppose a projectile is traveling along a trajectory. At the first large peak the shadowgraph results. But the rest of the film is raised close to the threshold of exposure. This is called "presensitization" and is often used by photographers to increase

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film speed.

An exaggerated case is shown in the sketch (Figure 30). As each successive maximum occurs, a partial exposure occurs on top of the previous one. This produces successive shadows. Aberdeen has had some trouble with this.

On the other hand, adding damping, even under the best conditions, adds inductance as well as resistance. The whole effect is to reduce the light output as may be seen again from Figure 25. The desired smoothness in the decay must be balanced carefully against the probable undesireable effects.

Purely as a sidelight it is interesting to present some calculations based on the energy input. Prescott, Melton, and Gayhart (1) note that if we assume (a) the discharge to happen so rapidly that practically no air escapes from the enclosure during this time, (b) the size of the gap as one millimeter in diameter and two and a half millimeters in length, and (c) take the usual specific heat constants for air at constant volume, each joule of energy put into the gap would raise the temperature 580,000 degrees, and the pressure 1700 atmospheres. Now obviously this is extreme. Much, probably most, of the energy put into the spark goes out as heat to the walls and electrodes, and in change of state transitions in the materials involved. A certain small amount goes out as sound, and relatively little as

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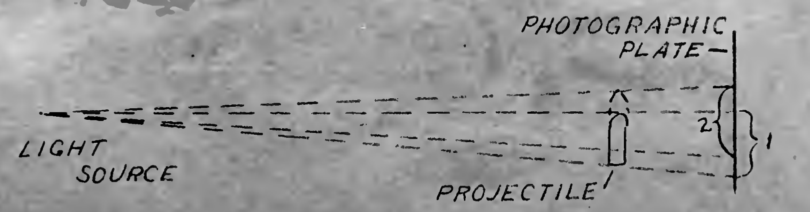

FIGURE 30
PRODUCTION OF SHADOWS BY LIGHT OSCILLATION

light. Suits has calculated the amount of sound energy in such discharges as on the order of 10^{-1} to 10^{-2} watt seconds. It is doubtful that his assumption of a constant spark temperature is valid and particularly in this case of a confined gap. However, the order of magnitude of the sound energy is probably somewhere near to that mentioned. This is, relatively, a small part of what must be expended in the gap.

It would be of interest to know the temperature of the gases in the gap. Several methods of measurement have been proposed but none so far has seemed practical. Dr. Dieke, of this University, has said that in probably six months it may be possible to make an estimate using the shift in prominent lines in the spectrum, but to date the method is not far enough advanced to permit this. If successful, this seems to offer the most practical answer to the problem.

Some additional negative information was acquired during the progress of these tests and is reported here purely as a matter of interest. Dr. Anderson of the University of California has been working with the so-called "exploded wire" where a large capacitance is discharged through a fine wire which vaporizes at the start of the discharge. He has found that the light output goes up if the wire is slightly covered with powdered sulphur. Although the case is somewhat different, the Liebessart gap was dusted with powdered sulphur.

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There was no apparent gain, although the spectrum might have conceivably be changed.

Mr. E. L. Gayhart, of the Applied Physics Laboratory, has made a considerable number of attempts to change the spectrum for special purposes. Among these experiments were changes of electrode. This included the making of rock salt electrodes in an attempt to get the sodium yellow doublet. These changes made no apparent difference in the spectrum. As a last attempt, the enclosure was filled with common salt. This produced the opposite effect. The resulting spectrum contained a dark space at the wavelengths at which the sodium lines would normally appear (the absorption spectrum). Thus in a short time spark, it appears that the electrodes have no particular effect on it. Other authorities state this same conclusion. (12)

2.6 Standardizing

In order to have some standard to compare with, or to reduce these results to some understandable terms, it was decided to attempt comparison with some standard lamp. For this purpose a standard 500 watt projection lamp was used. To put the steady output onthe photo-cell would not serve the purpose due to regulation in the power supply, fatigue in the photo-cell, etcetera.

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By this comparison the intrinsic brilliance (intensity per unit area) of the spark compared to the lamp was 92700 to 1. Now it must benoted that this is only in the spectral region of the 929 photo-cell. This does not compare in any other spectral region nor does it compare total radiation to all wavelengths. For this purpose it would be necessary to have a radiation plot of the relative intensity at various wavelengths, which plot is not available. For our purposes, however, the spectral region of the 929 photo-cell more nearly approximates film, so that this is used as a basis.

It is interesting to note the position of this spark on the table of common light sources. Fruengl gives 10^7 - 10^8 candles per square centimeter for his type of open spark in a gas filled bulb. This type of gap gives on the

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CHAPTER III

THE LIEBESSART GAP UNDER REPETITIVE PULSE CONDITIONS

A great deal of information basic to the operation of the Liebessart gap was derived from Chapter II. However, it was desired to investigate operation under a condition of repetitive pulses and even more specifically -- shaped pulses For this purpose the same gap was mounted in the output circuit of an aircraft type of radar pulser.

3.1 Apparatus

The apparatus used was essentially the same as that in Chapter II. The oscilloscope used was the same model as used previously although not the same scope. It did not have the extra high voltage power supply for post acceleration.

In this part of the investigation due to the lower energy in the spark, the photo-multiplier was used extensively. However, to prove the validity of the results they were compared with the results from a 929 photo-cell. There were no measureable variations (other than amplitude) between the two types of pick up.

The filters used in the first part were not available in the second part so that total radiation only could be measured. It is considered that in general the previous relations between the different spectral regions remained the same. This is considered a valid assumption, although at low powers and large gap enclosure sizes, there might be some spectral shift

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from the foregoing results.

The circuit diagram of the modulator used is shown as Figure 31. It was triggered from a synchroscope to give fairly good results. The repetition rate was varied over the range from 270 cps to 1450 cps.

3.2 Procedure

The parameters of gap length, enclosure diameter, and voltage applied, were varied as before. In addition, frequency of repetition became a parameter as well as the shape of the pulse.

The results were meant to serve as a check on the results of the preceding chapter as well as to find the effects of the two new parameters. The usual method was to vary one parameter at a time and determine the results. This was as a whole a more difficult procedure than before, due to the nature of the equipment and the low power input to the spark.

3.3 Test Results and Discussion

Within the limits of the tests, it can be said that in general the effect of changing gap length and diameter as deduced under single pulse conditions hold in this repetitive case as well. It is not easy to judge the results with respect to these parameters. The curves of Chapter II will shrink in toward the origin with decreasing power input. This is shown on Figures 18 and 20. Therefore, for low power in-

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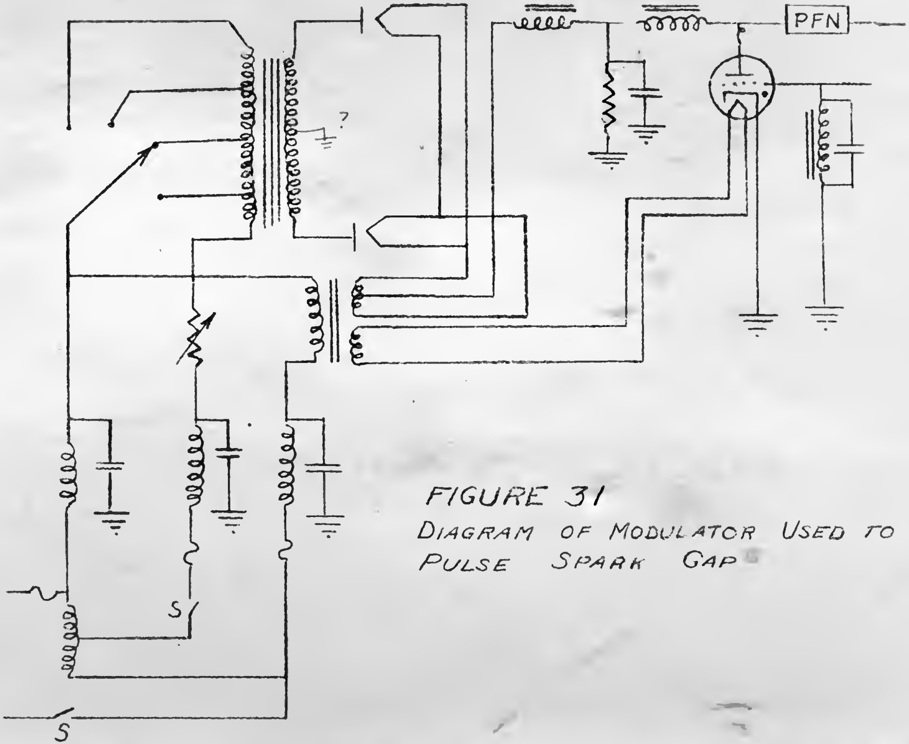


FIGURE 31
DIAGRAM OF MODULATOR USED TO PULSE SPARK GAP

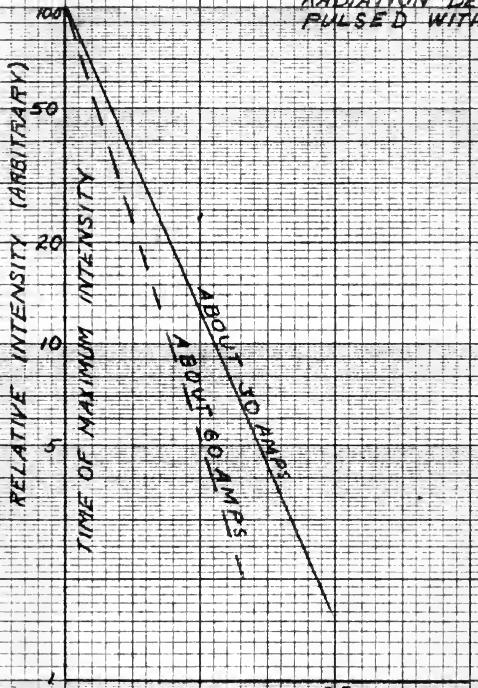
puts the optimum gap length and diameter become quite small. Such small sizes were notaattainable with the facilities at hand.

This is to say that the gaps used were all relatively large. Such a condition produces a very low efficiency of conversion to light. The variation of intensity with gap parameters would be of quite small order since the curve in this region is relatively flat and has only a very slight slope. (See Figure 20). Within these limitations the general effect does seem to hold.

An attempt was made to compare the slope of the rise of radiation and the slope of the current pulse rise. As nearly as could be determined, these were the same. This was not a very accurate measurement. It would require a much higher sweep speed and a higher frequency response of the amplifier than was available to determine this exactly. The observed traces, subject to the foregoing limitation, would tend to show that the possible upper limit of the rate of rise of radiation postulated in Chapter II has not been reached. This point requires further investigation.

In Figure 32 will be seen the plot of the radiation decay for the pulse resulting from a .1 micro-second current pulse. There was no apparent change in the decay rate when the repetition rate was changed (with input held constant).

FIGURE 32
RADIATION DECAY FOR GAP
PULSED WITH .1 μs PULSE



This was true through the range from 250 cps to 1500 cps. There was no apparent effect due to residual ionization throughout this range. The Naval Ordnance Laboratory has stated that there was no residual effect observed through a range several times the one mentioned above.

It will be noted that the decay rates change fairly radically as the current input is increased. This probably occurs because the pressurizing of the gap increases rapidly with increasing current at low input levels. We have shown previously that the decay steepened as the presumed pressurization increased.

The oscilloscope traces of the light pulse produced by the .1 micro-second pulses are shown as Figures 34 and 36. Figure 34 is paired with Figure 33 which shows the .1 micro-second current pulse applied to the gap. Figure 36 is paired with Figure 35 which shows the one micro-second current pulse. These tend to confirm the fact that the majority of the light energy is generated as a result of the first surge. They also show on close inspection that the .1 micro-second pulse produces a spark radiation which approaches .8 of a micro-second. Combining what is known from the previous part of this paper and what the decay curves show for this case, it can be said that a higher input current would produce steeper decay and that we could well approach small fractions of a micro-second

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It will be noted that the decay rates change fairly radically as the current input is increased. This probably occurs because the pressurizing of the gap increases rapidly with increasing current at low input levels. We have shown previously that the decay steepened as the presumed pressurization increased.

The oscilloscope traces of the light pulse produced by the .1 micro-second pulses are shown as Figures 34 and 36. Figure 34 is paired with Figure 33 which shows the .1 micro-second current pulse applied to the gap. Figure 36 is paired with Figure 35 which shows the one micro-second current pulse. These tend to confirm the fact that the majority of the light energy is generated as a result of the first surge. They also show on close inspection that the .1 micro-second pulse produces a spark radiation which approaches .8 of a micro-second. Combining what is known from the previous part of this paper and what the decay curves show for this case, it can be said that a higher input current would produce steeper decay and that we could well approach small fractions of a micro-second

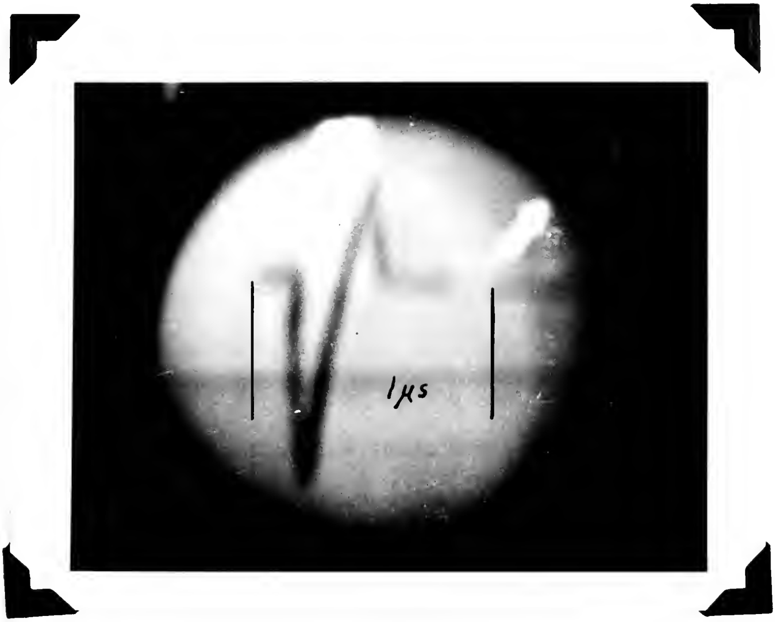

Figure 33

Figure 34

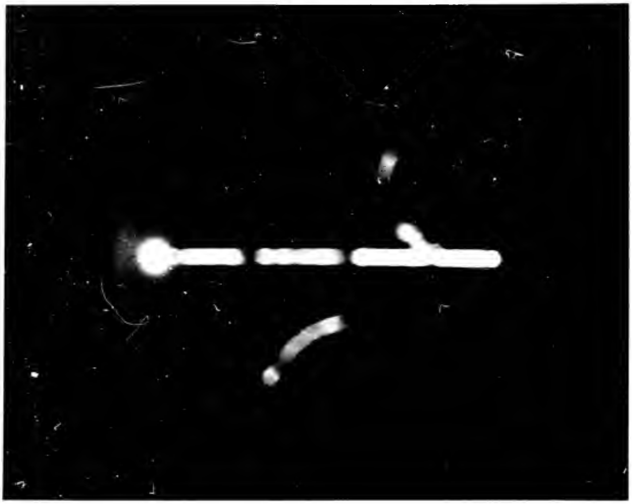

Figure 35

Figure 36

Figure 35

Figure 36

if more power were available. The currents used varied from about 30 to 60 amperes. The oscilloscope pictures also tend to prove that the maximum light output tends to vary as a more or less direct function of the current.

The amount of wear a gap of this type will stand should be mentioned here. The controlling factor is the amount of erosion or "blow-out" occuring to enlarge the channel in the insulator. In the type of material used by the author, very considerable enlargement, which had a pronounced deleterious effect on the output light, occurs at 300 to 600 flashes at high power and small enclosure channels. With a decrease in power or an increase in enclosure sizes the life is extended. However, a new type of enclosure consisting of a specially formed and baked soapstone insulator has just been introduced which has a greatly increased life. No exact figures are available on the increased life but it is thought to be many times that of the glass bonded mica insulator.

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CHAPTER IV

FLASH LAMPS

A spark provides an excellent point source, but without some considerable modification it cannot be used as a line source such as is needed in an interferometer. For this purpose a flash lamp is needed. As was pointed out in the spark, the spectrum of the discharge depends on the gas and is to some extent a function of the intensity -- that is the prominent lines shift with intensity of the discharge. For photographic purposes, a more desirable spectrum can be produced with control of the filling gas. The efficiency of conversion into light energy is not greatly improved from the Liebessart spark however, and the intrinsic brilliance (that is intensity per unit area) in most cases is actually lowered in comparison with this spark. The efficiency as against an open spark is, of course, much greater.

4.1 Types of Flash Lamps

There are relatively few flash lamps available commercially. All are an outgrowth of Edgerton's original flash lamp. General Electric Cmmpany is the only manufacturer producing any variety of these, but very little information is available from them beyond the spectrum to be expected. There are no published characteristics available except in one instance. This is for the General Electric Photoflood. The

Stroboflash is not described in detail, but evidently consists of a radio frequency high voltage supply, condenser, triggering circuit, and an FT-130 flash tube which will be described later. The time function of this combination is shown as Figure 37. General Electric flash tubes are manufactured on practically a model shop basis, and there exists a considerable variation from tube to tube according to the Naval Ordnance Laboratory. General Radio also manufactures a complete unit (Strobolume) using a stroboscopic type of light about which very little information is available. Germershausen has described what is evidently an expansion of this. (13)

Flash lamps are finding wide uses outside the ones discussed here. Advertising photographers are using some of the very large ones for commercial work, with a consequent saving of power. Westinghouse manufactures one large Krypton tube for flashing lighting of runways. This is a very large tube whose duration above 1/3 peak runs from 12 to 25 micro-seconds depending on input power (16). Krypton is claimed to be highly efficient when used in such lamps but is very expensive compared to argon.

General Electric flash tubes are manufactured in several series depending on their rating. The first number of the three digit numbers denotes this series. In addition there is one lamp not designed as a flash tube but which if often

FIGURE 37

TIME-INTENSITY FUNCTION - GE PHOTOFLOOD (AS PUBLISHED)

ly artificial when used in wood. Since this is very [illegible]

passable to dig it.

General Alonzo Clark ([illegible]) [illegible]

varies depending on their location. The first [illegible] of the

three ditch systems [illegible] this system. [illegible]

is one long one [illegible] of a [illegible]

used as such. This is an AH-6 mercury tube, designed as a high intensity lamp for normal lighting practice. The following table lists a number of the more common flash tubes with a brief description of each. Several of these are shown in Figure 38 (Supplied by Naval Ordnance Laboratory).

TABLE II

FT 108 - Small quartz tube similar in size to AH-6 Filling is Xenon (85%) - Hydrogen (15%)

FT 121 - Fairly large tube about 8" long. Constructed of pyrex with inner liner of quartz. Filled with Argon and Hydrogen. Number 2 in Figure 38.

FT 127 - A large quartz tube, 9" long, ½" outside diameter. Filled with Xenon and Hydrogen. Originally designed for California Institute of Technology. Number 1 in Figure 38.

FT 125 - Essentially an FT 127 twisted into a spiral and placed in a sealed beam mounting. Number 5 in Figure 38.

FT 230 - A short gap (on the order of 2mm) in Xenon-Hydrogen filler. Quartz tube. Number 3 in Figure 44.

FT 130 - Essentially an FT 230 placed in a sealed beam mounting.

FT 220 - A short gap (on the order of ½ mm) in Xenon-Hydrogen filler, tungsten electrodes, large quartz tube.

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FT 220 - A short gap (on the order of ½ mm) in Xenon-Hydrogen filler, tungsten electrodes, large quartz tube.

FX 1 - Two new lamps being developed by Edgerton. Assumed
FX 2 - to be in the order of FT 127 but with twice the efficiency.

British Arditron - A long gap, circular plate electrodes, Xenon filled lamp, in hard glass. About the size of a projection lamp. Number 4 in Figure 38.

AH-6 - A quartz tube, 1" long, ¼" outer diameter, mercury in nitrogen filler.

The spectrum of most of these correspond roughly to a black-body at 7000° K.

4.2 Characteristics

The flash tube in operation is essentially an elongated spark through a gas filled tube. As such, it displays a great many of the same characteristics as a spark. In many of the flash tubes, the tube is spiralled and placed in a sealed beam type mounting for convenience and reduction in space. Tubes are either glass or quartz. Quartz is much preferred because the life is much greater and the permissible power input is much higher. The spectral transmission of quartz tends to the ultra-violet. In any flash tube the upper limit is determined by the physical damage to the tube from heating. "Crazing" takes place if too much power is put in and ruins the tube. Quartz "powders" in time with normal use. This

[illegible] Assumed

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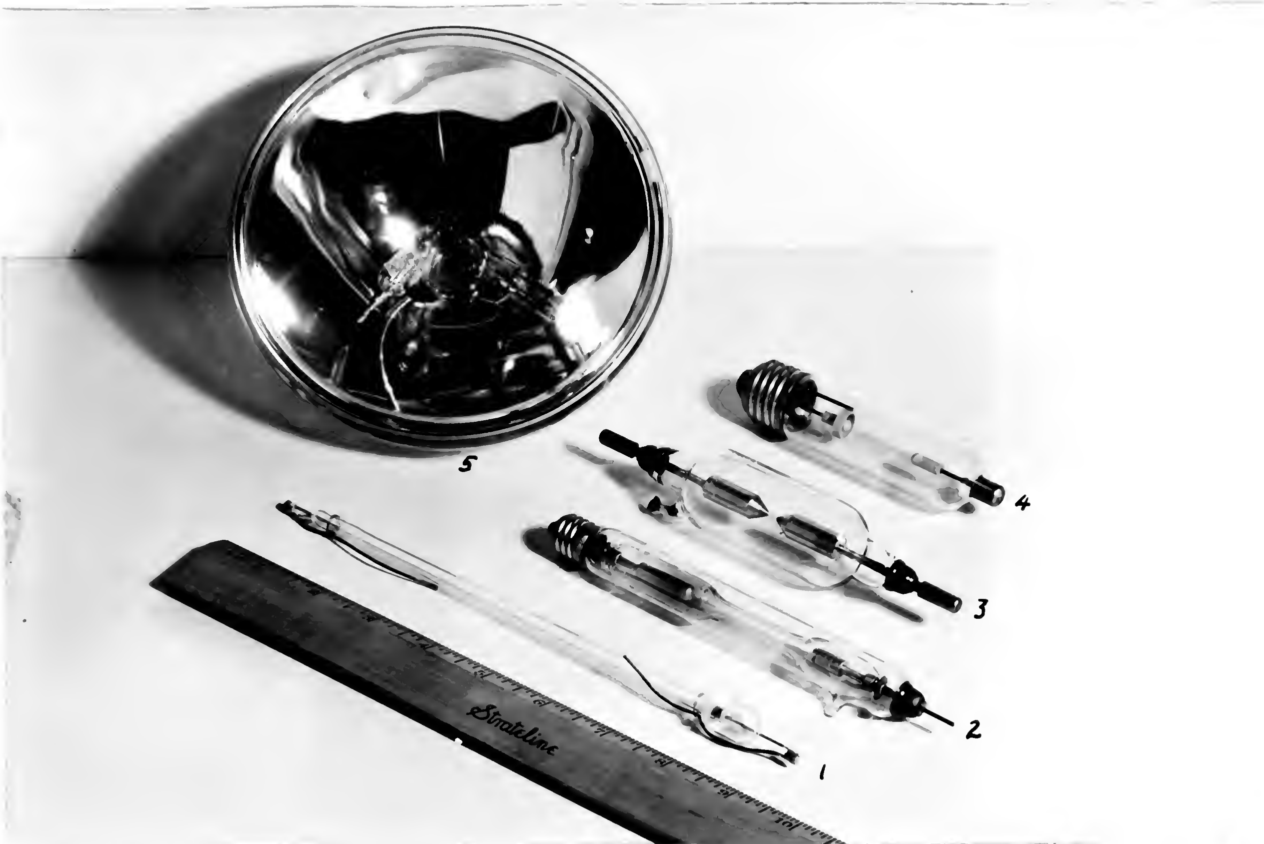

(COURTESY NAVAL ORDNANCE LABORATORY)

FIGURE 38

FIGURE 38

(COURTESY NAVAL ORDNANCE LABORATORIES)

deposit on the inside of the tube cuts down the light after a while. Some of the latest tubes are arranged to have the powder deposit on the bottom and keep the tube clear.

When a tube gets old, it will occasionally misfire. This is due, at least partly, to released contaminating gases. In the case of pulse lines with thyratron firing, this is especially serious since the reflected wave travels back up the lines producing very high voltages and also ruining the thyratron -- probably by driving electrons back into the emitter. The life of these flash tubes may be measured in terms of number of flashes and power input. They run from about 10,000 flashes on up for a rated input.

Figures 39 through 41 are oscilloscope traces of the light pulse from three flash tubes when connected in the circuit of Figure 3 in place of the Liebessart gap. Figure 39 for the FT-108, Figure 40 for the FT-121, and Figure 41 is the light pulse from the AH-6. These traces were made under the same sort of conditions as those for Chapter II. The decay plots for these are shown as Figure 42.

No attempt was made to investigate the flash tubes in the same manner as the Liebessart gap. The above photographs were made merely for information. These pictures do show some interesting characteristics. The AH-6 apparently has a relatively high resistance and operates more in the nature of

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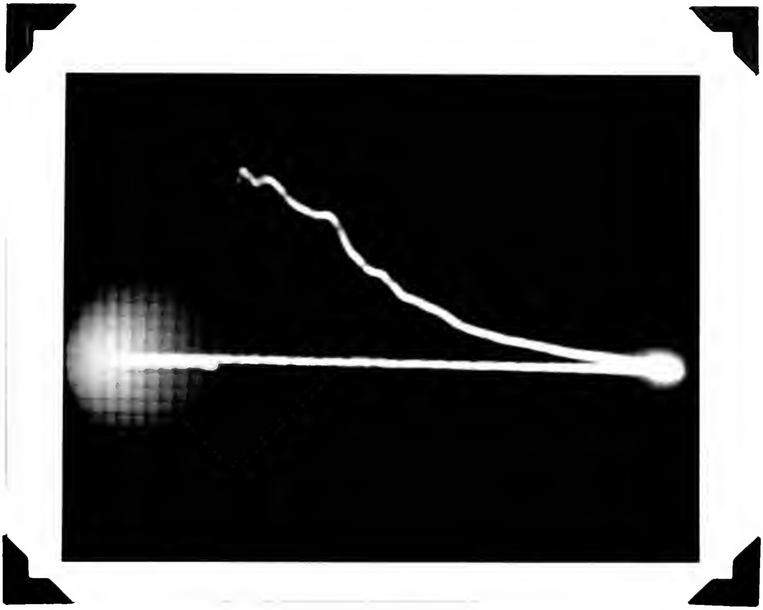

Figure 39

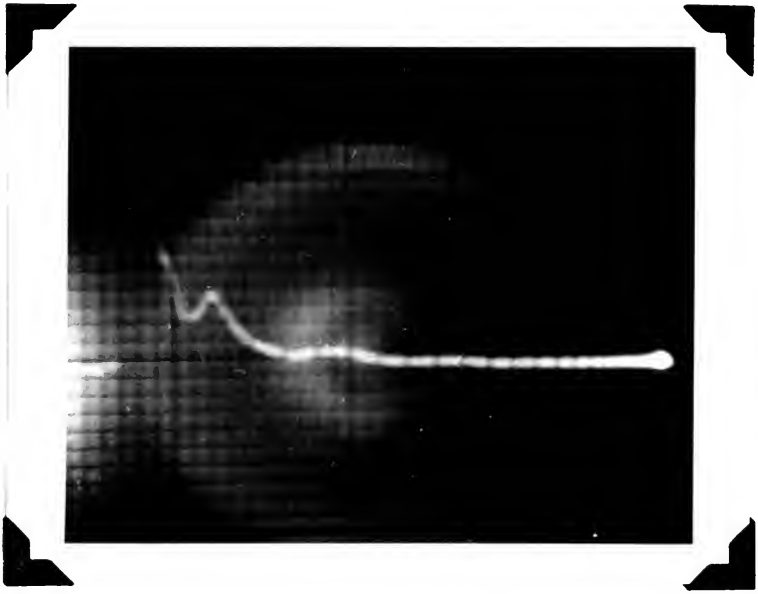

Figure 40

Figure 39

Figure 40

Figure 41

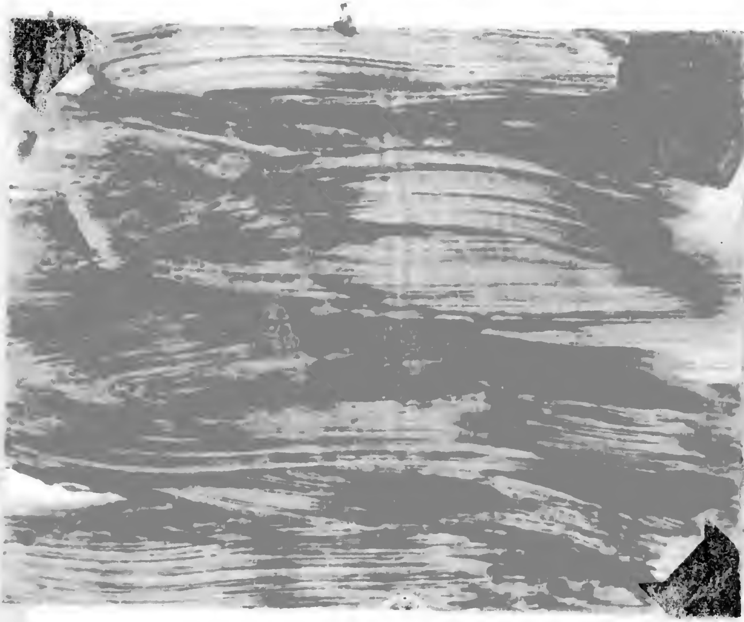

Figure 41

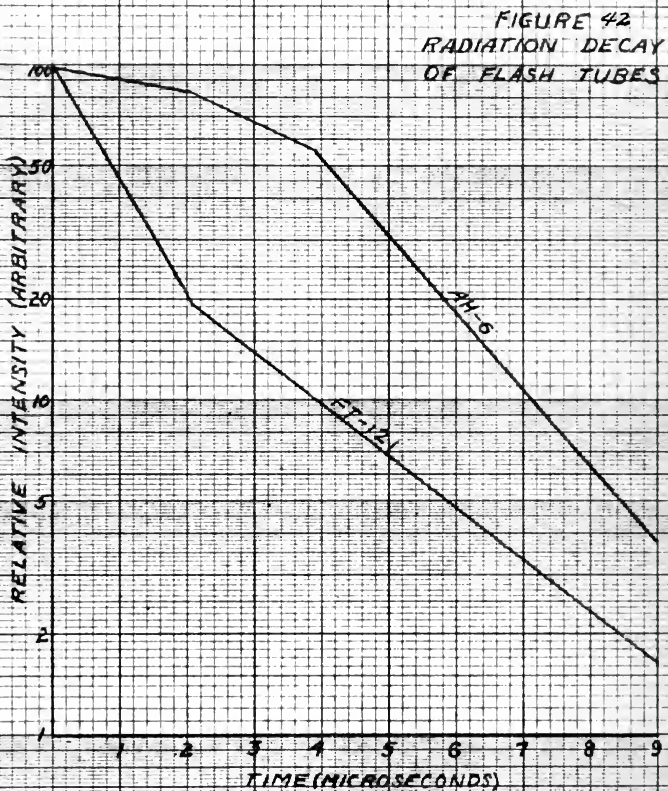

FIGURE 42
RADIATION DECAY
OF FLASH TUBES
100
50
20
10
5
2
1
RELATIVE INTENSITY (ARBITRARY)
1
2
3
4
5
6
7
8
9
TIME (MICROSECONDS)
AH-6
FT-12

a resistance load. The decay is relatively slow. The FT-121 appears much like the spark. The pronounced maxima on the decay of the FT-121 bears a striking resemblance to the characteristics of the General Electric Photoflood (Figure 37). The relative candle power is shown in Table I as determined by comparison with the standardizing source mentioned previously. Their over-all light output compared with the spark gap is as follows: FT-108 - 1.1 to 1 FT-121 (at a low rating) - 2.3 to 1.

These traces bear out a point which is important to design -- namely that the total light output from one of these tubes, although they are considerably larger, is of the same order of magnitude as the spark whose area is much less. At the best it is probably that, excepting the FX-1 and FX-2 about which nothing much is known, the most that can be obtained is about twice the Liebessart gap for the same conditions. The per unit area intensity of the flash lamp is much less.

These tubes have one big advantage over the Liebessart spark. Their actual resistance is higher and they show much less of the negative dynamic resistance so marked in the spark. Actual resistance for these lamps runs from about .5 ohm to 8 ohms or better. They are therefore much better

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suited to a pulse line input and matching is not so critical or so difficult. They still show a highly variable I-V characteristic over the duration of the pulse. Carlsen and Pritchard state that they display a negative resistance characteristic over the first part of a long (300 micro-seconds) flash and a rising characteristic thereafter. (21) Edgerton has found that at high loadings the ratio of voltage to peak current is approximately constant.

The actual radiation decay can be controlled to some extent by the filling. Hydrogen has been found to have a quenching effect, which is of considerable help when attempting to get short time durations. As the filling pressure is decreased, the continuum disappears leaving only strong lines in the spectrum. Most of these flash-tubes are operated at from one to four atmospheres pressure. The increase in efficiency with pressure is not so great above five centimeters. (12) Xenon filling produces one of the most efficient types. In addition Xenon has a very desirable spectrum with much visible radiation -- where most films are sensitive.

Carlsen and Pritchard state that as a rough rule the duration of flash of a Xenon tube (to 1/3 peak on decay) is equal to 20 $\frac{C^{.69}}{V^{.625}}$. It is doubtful that this holds too well at very short durations but it does indicate an effect noted

with the spark -- that high voltages are needed for short durations. The same authors state that Argon produces the shortest flash.

The maximum peak output as before appears to be proportional to the first power of the current. This is only roughly true, since it may vary quite widely above or below this median with varying efficiency.

Both the spark and the flash tubes show a discouraging trend as their light output is pushed up higher. The curve of light output versus voltage applied begins to level off. This is noticeable in Figure 17 for the small gap. It will occur with all these light sources, but the level at which it occurs may be raised by determining what factors affect it. From a study of various authors and some investigation, it appears probable that a relatively low efficiency source may be pushed higher in absolute output when operating at very high levels than can sources which start out at high efficiencies. A parallel might be drawn with the gain of an amplifier. At high gain the band pass is much less than at a lower gain, but lower gain is accepted in pushing the upper limit higher up the frequency scale.

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Flash tubes have one other advantage in that they are more easily placed in a reflector than a spark gap and are less cumbersome to design for. On the other hand, each tube

has an upper input limit while the spark gap is restricted only by the power source.

Some difference will be found between any discussion here and the discussions listed in the references. This is largely a point of view. Most of Edgerton's, Germershausen's, and other's work has been from the point of view of fairly long exposure time, in contrast to what is considered here. Correctly enough, almost all of the foregoing have considered the integrated light output over the whole period as a measure of output.

The point of view expressed here considers only the highest intensity portion and that over the shortest possible interval of time. As has been pointed, out, the "effective duratinn" under these conditions is not exactly what the output light pulse would seem to provide. It is usually somewhat less, and experience indicates it bears a close relation to the initial peak and its shape. Considered in this light, most of the previous investigations are deficient in that they do not extend down into the very short duration high input regions. Extrapolation from existing curves would be inaccurate in most cases since the behavior often changes fairly abruptly. This is not meant as a detraction nor does it mean that a great many facts can not be inferred from these results, but it does imply that investigation must be carried

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farther. Some thorough study should be made of these aspects and probably is being made by some users.

It is postulated that a considerable portion of the effects noted in Chapter I will occur with these lamps. Certain of these are basic to any short time discharge. Such effects as variation in decay time between wavelengths undoubtedly exist. It is probable that the strong lines in the lower part of the spectrum for any lamp have the most rapid decay. The time lag between firing and the beginning of radiation will exist, but the effect of different gases and different pressures is not known. It is doubtful if the nature of the gas will affect it much.

CHAPTER V

MULTIPLE FLASH ARRANGEMENTS

This paper would be incomplete without some mention of multiple flash arrangements. These range all the way from two sources arranged side by side and fired with a suitable delay, to a number of lamps flashed in rotation at high repetition rates. Most of these developments are the result of wartime born equipment and research.

Almost all multiple flash equipments have two points in common. They operate from a modified radar pulser, and they require considerable power, A repetitive pulse from such a source has a distinct advantage. By careful design the pulse shape can be controlled to almost any shape desired, and the duration can be designed to almost any duration.

Because they have such a small duty cycle, it now appears that the hydrogen thyratrons will pass on the order of kiloamperes in these circuits. The design requires no particular impedance matching to the load, although as Germershausen (13) points out, a more desirable situation would be to have a much higher resistance in the flash lamp. New flash lamps are being designed with this in mind.

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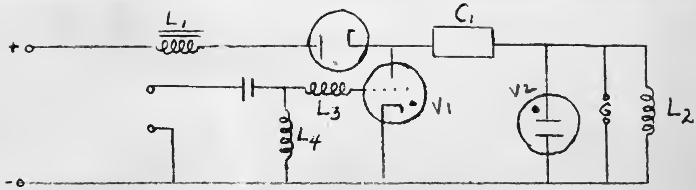

FIGURE 43
MULTIPLE FLASH CIRCUIT

a 5C22 thyratron, V_2 is the flash lamp; L_2 is a recharging by-pass; and G is a gap to protect against overvoltage operation. Inductive controlled charging is used because of the much higher efficiency. This becomes important when lamps are running at thousands of cycles per second. Efficiency with inductive charging is on the order of 90 per cent.

The equipment described in the foregoing reference (14) was built and operates at the Naval Ordnance Laboratory. Actually six lamps are operated in two banks to provide lighting for moving picture photography up to 16,000 frames per second. This takes about 20 kilo-watts minimum. With this system the FT-125 has been extensively used. The FT-125 has a rated input which must not be exceeded. In order to keep within this limitation, one must either cut down the energy per flash or reduce the number of flashes. The latter system is used. For instance, for 8000 frames per second the two banks operate for alternate frames, so that each bank operates at 4000 flashes per second.

This poses some very special synchronization signal between the camera and the lamps. The synchronization signal is taken from pulses developed by the shutter rotation. These are generated by small iron wafers attached to the driving pulley on the camera. The wafers pass through a magnetic circuit, varying the reluctance. The pulses thus generated are passed

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through a divider circuit which produces two outputs, each at one half the original frequency. The two outputs are exactly 180° out of phase so that each pulse corresponds to a frame.

Each flash lamp has its own network. The pulses are delivered to each of these six networks. On arrival, the pulses are put through video amplifiers which produce outputs suitable for triggering the thyratrons. The amplifiers are "blocked" until an unblocking voltage is applied. The unblocking signal is supplied from an "interlacer" and sequence unit. This unit can be set for a successive pattern and duration of operation of any one or any set of flash lamps. For example, if a slowly moving object were crossing the front of a bank of lights, the lights could be set to operate for successive periods when the object was directly in front of certain lamps. This permits any combination of lighting desired.

These systems all require relatively large amounts of power for short periods. The high-speed stroboscope described in reference (13) using only one lamp requires about 3.3 kilo-watts. It must be pointed out that film characteristics and the term "effective duration" enter the problem again. Also it need be remembered that the larger the area illumina-

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On a small scale, the sort of thing that was done in Chapter III is exactly parallel. The Naval Ordnance Laboratory system just described represents the most elaborate and advanced system in use at the moment. It also represents the sort of short duration high intensity lighting that is becoming increasingly important. This is a relatively new field and is yet in its infancy.

The design of these systems presents some special problems for camera design and some difficult problems in synchronization. However, the limiting factor at present is the light output. This is dependent on better flash lamps and greater power input in shorter pulses. So far the above system has not been adequate for all the investigations in progress requiring flashing lighting.

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CHAPTER VI

CONCLUSIONS - DESIGN CONSIDERATIONS

It is interesting to note some of the requirements for illuminants for high speed photography as drawn up by a sub-committee of the Society of Motion Picture Engineers.

1. It should cover an area to be photographed of 4 x 4 inches.
2. The variation in illumination from the center of the area to the corners should not exceed 2:1.
3. The minimum distance from the source to the area is 18 inches.
4. It should produce a minimum illumination of 50,000 foot-candles at the center of the area, although this may be raised to 100,000 foot-candles.
5. A color temperature of the source of approximately 3500° Kelvin is desirable.

Not all of these requirements are applicable to the particular type of lighting discussed here, but these do provide a guide. Most of them can be met by existing light sources. However, in requirement 4 the same problem stated in the beginning intrudes. Requirement 4 is undoubtedly not high enough for the very short durations discussed here. Again, as the duration goes down, intensity must go up. The problem resolves itself into two parts, getting the required time duration and raising the intensity.

6.1 Single Pulse Source

Any design of course depends upon the requirements put

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6.1 Single Pulse Source

Any design of course depends upon the requirements put

on it. Considering first the design of a single pulse source, one must decide whether a flash lamp or a Liebessart gap is to be used. Some of the advantages and disadvantages can be listed. Flash lamps are expensive. A gap can be built fairly cheaply. The level to which a flash lamp can be raised in short time pulses is not exactly determined. A spark gap has no predictable upper limit. The spectrum of a flash lamp on the whole is more favorable and the lamp is more easily placed in a reflector. Line or point source requirements must be satisfied in any decision.

If a Liebessart gap were to be used, based on what was presented in Chapter II and III, certain conclusions must be drawn. First, the gap must be small in diameter and in length, but such dimensions must depend on the energy input. Secondly, to get a high peak the highest practicable voltage must be applied. Thirdly, the minimum damping possible should be used. This variable cannot be predicted with any certainty and would depend on the condenser and circuit characteristics. Fourth, the capacitance must be reduced to the lowest permissible value depending on the power source and energy necessary.

In a practical design at present a radio-frequency power supply would undoubtedly be used. A 30 kilo-volt supply is easily available. The capacitance would be reduced to .01 micro-farads to get the same energy storage as .1 micro-farad

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In a practical design at present a radio-frequency power supply would undoubtedly be used. A 30 kilo-volt supply is easily available. The capacitance would be reduced to .01 micro-farads to get the same energy storage as .1 micro-farad

at ten kilo-volts.

Taken altogether these would call for a prediction of a diameter of about .02 inches for the channel diameter and a gap length of about .03 inches. These might be varied slightly to find exactly the right point for optimum results. It is considered that the inductance can be kept to about .15 micro-henry by proper design. Therefore, the frequency of oscillation can be brought fairly close to ten megacycles. This would give an output light pulse on the order of .3 micro-seconds (to the ten per cent level). If filtered for blue, this might be brought down to .18 or .19 micro-second. The "effective duration" might well be on the order of .08 or .10 micro-second. The total damping in the circuit should probably be about .75 ohm, but this is not predictable.

As a note in passing, radio frequency power supplies possess great advantages for this type of operation. They are compact and light in weight. They are not dangerous to handle. They do not suffer damage nor provide a large power drain under short circuit conditions. The only disadvantage is the relatively long time required to recharge the capacitor.

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It appears that a long gap would produce the best results for high voltages. An FT-127 fulfills these requirements and in addition possesses a desirable filling gas. The same order of magnitude in results both as to duration andlight output could be expected as in the spark gap.

6.2 Pulse Line

The possibility of using pulse forming networks as approximately matched transmission lines must not be discounted. There is now a projected design of such character under discussion at several laboratories. A possible sketch is shown in Figure 44. The apparatus in question is to consist of two concentric copper cylinders separated by a barium type dielectric with a dielectric constant of 1200 and is to produce a .1 micro-second pulse. It is planned to use it with a radio-frequency power supply of 30 kilo-volts or better. If the characteristics of this line are calculated, the impedence is found to be .8 ohm, and the capacitance .026 micro-farad. It would store 10.3 joules with 30 kilo-volts applied.

Really it is a misnomer to call this type of design a line. It is more accurate to consider it a condenser with associated inductance and resistance. The design possesses certain inherent advantages. The inductance is a minimum. Physically the unit is very compact. Resistance can be added

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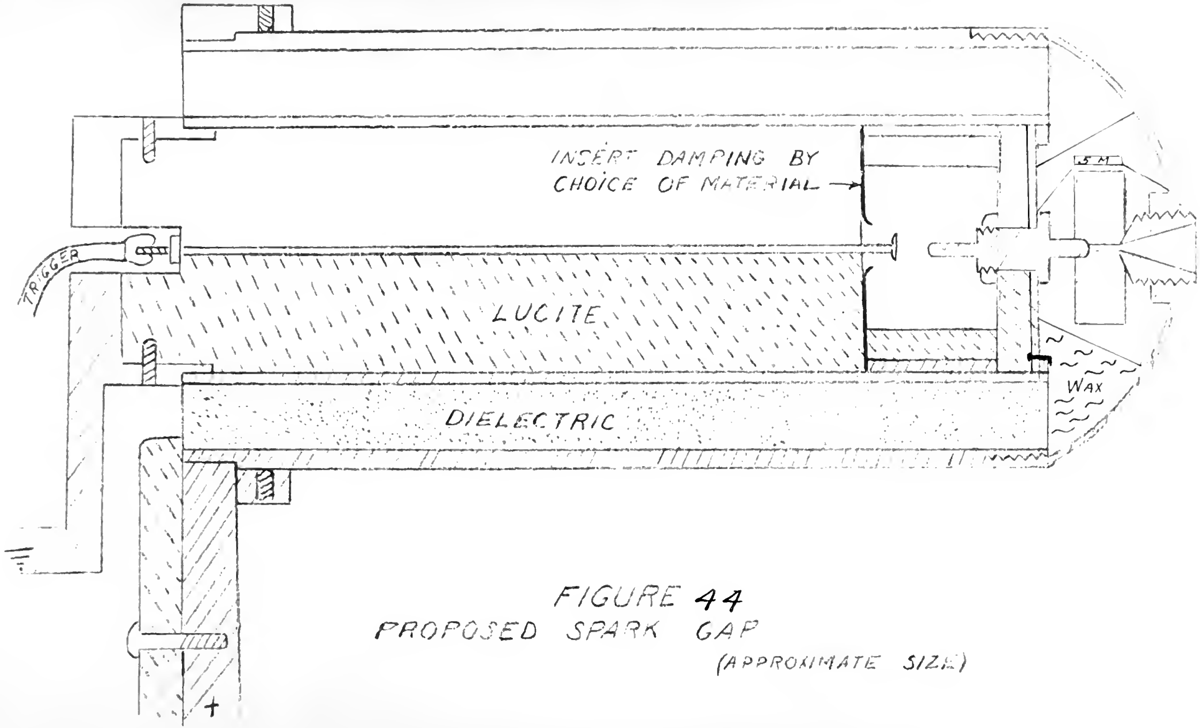

FIGURE 44
PROPOSED SPARK GAP
(APPROXIMATE SIZE)

by changing the characteristics of the rear plate. Unfortunately considerable doubt exists that the dielectric constant will remain constant at high voltages. Some early experiments in this respect have produced some disquieting results. The cost of such construction is quite high and so far has been the chief deterrent.

In all these designs it is considered better to use an auxilliary gap for firing single discharges. This is primarily a matter of keeping the inductance to a minimum. The wiring required by a thyratron cannot but add inductance. Furthermore in Figure 44 physical space limitations would prevent any such arrangement.

6.3 Multiple Flash Designs

In the matter of repeated pulse operation, the flash lamp seems to be the best answer. The reflections on discharge are not so marked as in the spark in most cases. Ease of positioning and life probably are much superior. Spark gaps could be used, and it would be most interesting to compare their performance with that of flash lamps under identical conditions. But flash lamps inherently possess greater possibilities for this type of work. Flash lamps are only beginning their development. Efficiencies can and undoubtedly will be raised and resistances characteristics improved. However, design must be directed toward a lamp specifically

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designed for very short duration, repetitive pulses. In all cases radar type pulsing circuits modified for the particular conditions of operation will undoubtedly be used. It would be futile to attempt here to give details of such a complicated type of design with so many possible variations.

6.4. Standards and Development

The whole field of very short duration high-intensity sources is just now opening up. There are a number of auxiliary problems to be solved. For example, although this paper undertook, among other things, to reduce the light output to understandable comparative terms, there are actually no comparative standards used in this field. Some standard which can be easily and accurately reproduced is urgently required.

There are a number of promising lines of development for such a standard. One of these is an image converter. In this apparatus a sweep deflects an electron beam across the face of a tube just as in an oscilloscope. A photo-electric cell picks up the image of a light source. The output of the photo-cell controls the brightness of the line appearing on the tube face by controlling the accelerating voltages. In some of the modern tubes such as projection television tubes, the brightness can be made very high. The sweep presents no great difficulty nor does any other part of the

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circuit required. The main development appears to be needed in phosphors. Various adaptions of this for very short duration sources appear highly feasible, both for use as a standard, and possibly as a line source. Note that this could be made to approach a mono-chromatic line source.

The Kerr cell, although properly not discussed here, after some further development in size may be used in conjunction with these sources for making very short time photographs. The great handicap here is transmission, since the theoretical maximum transmission is 50 per cent and the practical maximum probably is in the neighborhood of 45 per cent of the total light.

At present there is very little in the nature of standard practice. Every problem must be considered as a more or less special development. The probable lines of advance run toward investigation and design of improved flash lamps and the adaption and/or development of new light sources such as the image converter. The field will undoubtedly make great advances in the next few years as it becomes more widely spread, particularly since the demand is increasing steadily in many lines of endeavor.

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